Workshop Report:
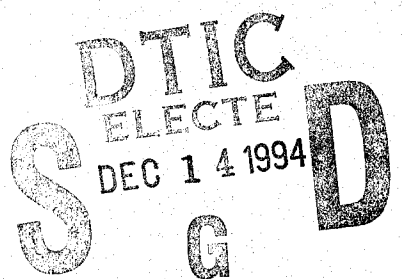# Measurement Techniques in Highly Transient, Spectrally Rich Combustion Environments

Todd E. Rosenberger

ARL-SR-18   September 1994

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Todd E. Rosenberger

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U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066

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13. ABSTRACT (Maximum 200 words)

With the emergence of advanced propulsion systems such as liquid propellant (LP), electrothermal-chemical (ETC), electromagnetic (EM), conventional hypervelocity, and in-bore ramjet, the measurement of combustion phenomena has become more complex. The data associated with these systems can be rich in high-frequency components, and share similar transient behavior. Measurement techniques associated with conventional solid propellant systems are not always capable of accurately recording these phenomena.

The accuracy of pressure and acceleration measurements in combustion chambers, barrels, and on-board projectiles has been compromised by the lack of a fundamental understanding of the effects of the mounting configuration and the mechanical and electrical components of the transducer on the integrity of the measurement. Consequently, the system development and technical understanding of the physical processes involved in the ignition and combustion of such advanced propulsion systems have been compromised. A workshop was needed to bring together experts from the aforementioned and related communities to disseminate knowledge of lessons learned and to discuss the techniques necessary to make high-fidelity pressure measurements in these environments.

This report will state the objectives, identify the participants who met to address them, provide a list of the technical presentations made, present highlights from these presentations and the discussions that they prompted, and end with conclusions and recommendations which came out of the workshop.

14. SUBJECT TERMS

measurement techniques, highly transient, spectrally rich, combustion environments, pressure measurement, high-frequency combustion characterization, pressure oscillations, liquid propellants, in-bore ramjet, RLPGs

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TABLE OF CONTENTS

LIST OF FIGURES

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1. INTRODUCTION

With the emergence of advanced propulsion systems such as liquid propellant (LP), electrothermal-chemical (ETC), electromagnetic (EM), conventional hypervelocity, and in-bore ramjet, the measurement of combustion phenomena has become more complex. The data associated with these systems can be rich in high-frequency components, and share similar transient behavior. Measurement techniques associated with conventional solid propellant systems are not always capable of accurately recording these phenomena.

The accuracy of measurements, specifically of pressure and acceleration phenomena in combustion chambers, barrels, and on-board projectiles has been compromised by the lack of a fundamental understanding of the effects of the physical configuration and the mechanical and electrical components on the integrity of the measurement. Current combustion chamber, gun tube, and on-board projectile measurements needed to characterize system response to these highly transient, spectrally rich combustion environments may be inadequate for modelers to characterize the theoretical response of system hardware to these harsh environments.

Consequently, the development and technical understanding of the physical processes involved in the ignition and combustion of such advanced propulsion systems have been compromised. Although the propulsion system examples noted are primarily in the gun arena, it is hoped that the expertise that exists in the rocket and ramjet communities may be brought to bear on this problem. A workshop was needed to bring together experts from the aforementioned and related communities to disseminate knowledge of lessons learned and to discuss the techniques necessary to make high-fidelity pressure measurements in these environments.

The request for a workshop examining measurement techniques in highly transient, spectrally rich combustion environments was submitted at the 29th JANNAF Combustion Subcommittee Meeting and later approved by the Executive Committee. The workshop was held 19 November 1993 at the Hyatt Regency Hotel, Monterey, CA under the auspices of the 30th JANNAF Combustion Subcommittee Meeting and was chaired by the author of this workshop report. This report will state the objectives, identify the participants who met to address them, provide a list of the technical presentations made, present highlights from these presentations and the discussion that they prompted, and end with conclusions and recommendations which came out of the workshop.

2. WORKSHOP OBJECTIVES

The workshop objectives were distributed to the participants in the call for papers and attendees for the workshop. The specific workshop objectives were the following:

- Outline the measurement challenges and problems associated with characterizing combustion environments in solid propellant (SP), LP, ETC, EM, conventional hypervelocity, in-bore ramjet, and associated technologies

- Survey measurement techniques appropriate for the measurement of highly transient, spectrally rich combustion phenomena in guns, simulators, and on-board projectiles of propulsion technologies including, but not limited to: SP, LP, ETC, EM, conventional hypervelocity and in-bore ramjet

- Recommend future measurement technology research areas.

3. WORKSHOP PARTICIPANTS

The general goal of the workshop was to assemble expert attendees, drawn from gun, rocket, ramjet, and related disciplines and representing government, industry, and academia, that would disseminate knowledge of lessons learned to the various communities represented and discuss the techniques necessary to make high-fidelity pressure measurements in these highly transient, spectrally rich combustion environments. The workshop call for papers and attendees was mailed to a large number of prospective attendees from the relevant disciplines. While representatives from the desired areas were in attendance, a wider representation from those areas probably would have added significant contributions to the workshop. The workshop attendees were:

G. A. Benedetti,
  Sandia National Laboratory (SNL)

Steven Brown,
  Martin Marietta

Mary Chan,
  Naval Air Weapons Center (NAWC)

David Kruczynski,
  U.S. Army Research Laboratory (ARL)

G. L. Mackenzie,
  Stone Engineering

John Mandzy,
  Martin Marietta

Kok Chung,
  Army Research, Development,
  and Engineering Center (ARDEC)

Arthur Cohen,
  ARL

Marilyn Cooper,
  PCB Piezotronics

James DeSpirito,
  ARL

Jerry Finlinson,
  NAWC

Robert Greig,
  GT-Devices

Albert Horst,
  ARL

B. L. Iwanciow,
  Stone Engineering

Gary Katulka,
  ARL

Roderick King,
  ARDEC

John Knapton,
  ARL

Neale Messina,
  Princeton Combustion Research
  Laboratory (PCRL)

Thomas Minor,
  ARL

Michael Nusca,
  ARL

Welton "Red" Phillips,
  Yuma Proving Ground (YPG)

Fredrick Robbins,
  ARL

Todd Rosenberger,
  ARL

Gabiel Roy,
  Office of Naval Research (ONR)

Ray Rychnovski,
  SNL

Mark Schneider,
  FMC

Neale Winsor,
  GT-Devices

Jody Wormhoudt,
  Aerodyne

4. LIST OF PRESENTATIONS

Eight papers were presented over the duration of the 4-hr workshop with time at the end of each presentation for questions and discussion. The workshop concluded with a 30-min period during which the participants attempted to come to some conclusions, or at least a consensus, on the major issues which were discussed throughout the session. In addition, this time was used to make recommendations for future measurement technology research investigations. Copies of the viewgraphs used in the workshop presentations are included in the appendices. The presentations were:

3

"Measurement Techniques in Highly Transient, Spectrally Rich Combustion Environments: Welcome, Workshop Motivation and Objectives," T. E. Rosenberger, ARL.

"Comparison of Pressure Measurements in Through Ports and Stepped Ports," R. E. Rychnovsky, Sandia National Laboratories (SNL).

"Measurement of Oscillatory Pressure Using Single Diameter and Two Diameter Transducer Cavities," G. A. Benedetti, SNL.

"Further Evidence of the Effects of Two Diameter Transducer Cavities on Pressure Measurements," J. DeSpirito, N. E. Boyer, T. E. Rosenberger, and J. W. Colburn, ARL.

"High Frequency Pressure Oscillations in the In Bore Ramjet Accelerator," D. L. Kruczynski and J. W. Colburn, ARL.

"An Optical Pressure Gauge For High Speed Measurements in the 10-250 kbar Range," J. Wormhoudt, P. L. Kebabian, and K. D. Annen, Aerodyne Research, Inc.

"Pressure Transducers for the Liquid Propellant Gun," Welton "Red" Phillips, Yuma Proving Ground (YPG).

"Fiber Optic Pressure Transducers," T. E. Rosenberger, ARL, for W. S. Walton, U.S. Army Combat Systems Test Activity (CSTA).

"Recommendations for Future Measurement Technology Research," Workshop Participants.

5. HIGHLIGHTS FROM PRESENTATIONS AND DISCUSSION

In beginning the workshop, the motivation and objectives outlined earlier in this report were presented by the workshop chairman, T. E. Rosenberger of ARL. He reminded the participants that the agenda for the workshop was directed mainly toward the measurement of combustion pressure in transient, high-frequency environments because the response to the call for papers resulted almost exclusively in presentations in this arena. Consequently, the decision was made to concentrate on this area of measurement technology.

Rosenberger began the presentation by pointing out that the combustion environment of conventional guns is traditionally characterized by relatively low frequency (< 10 kHz) data. On the other hand, the combustion environments of advanced propulsion systems such as regenerative liquid propellant guns (RLPGs), hybrid in-bore ramjets (HIRAMs), and early ETC guns using LP as the fuel, were characterized by transient, high-frequency (near-DC to 80 kHz) data. Examples of pressure-time (p-t) data for these systems are shown in Figure 1.

One of the most pertinent questions that one must ask of the data is whether they are an accurate description of the physical processes involved. During the past several years, questions have been raised concerning the adequacy of the measurement techniques used to quantify the combustion environments in these advanced propulsion systems. A general consensus throughout the measurement community is that some of the measurement techniques used to characterize traditional propulsion systems are inadequate for characterizing the "highly transient, spectrally rich combustion environments" associated with emerging propulsion technologies.
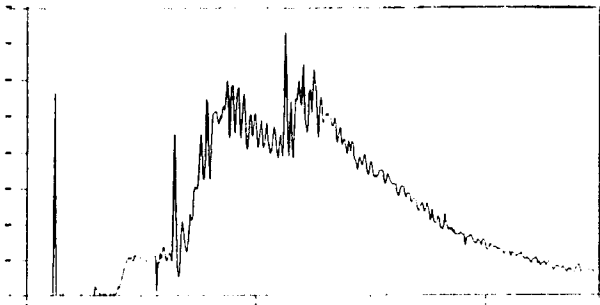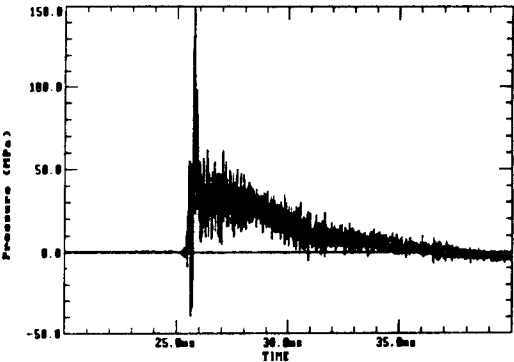
Figure 2 shows a block diagram of a typical measurement system. It consists of a transducer, mounting configuration, signal conditioning equipment, acquisition system, and associated instrumentation lines. One can associate a number of measurement challenges/problems with each area of the measurement system, though only a handful of the most pressing issues were presented here.

Rosenberger pointed out that vendor specifications for transducers were well above the requirements for conventional testing. Subsequently, parameters such a resonant frequency, acceleration, shock, and vibration sensitivity were not found to be a limitation for measurements like pressure and acceleration. However, as the frequency content of the data became higher and the environment more severe, the limits of the transducers were pushed, often beyond their capabilities. Consequently, vendor specifications like those mentioned must always be examined closely to determine the applicability of the transducer to the environment. It was pointed out that pressure transducers used in these environments have demonstrated a mortality rate much higher than those used in conventional testing. It was postulated that since the combustion gas temperatures are typically the same as those experienced in conventional testing, the cause of this phenomenon can be directly linked to excessive gauge vibration in the presence of the severe, high-frequency oscillations.

Regenerative Liquid Propellant Gun
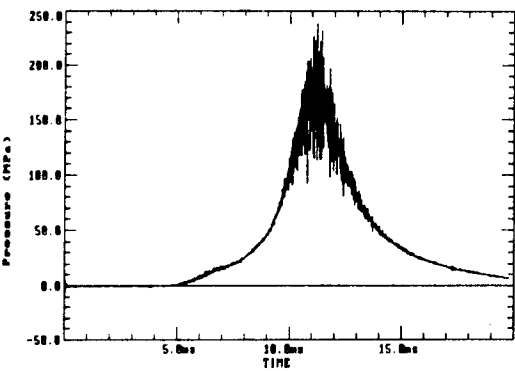
Inbore Ramjet

Electrothermal-Chemical Gun

Figure 1. Examples of highly transient, spectrally rich pressure-time data.
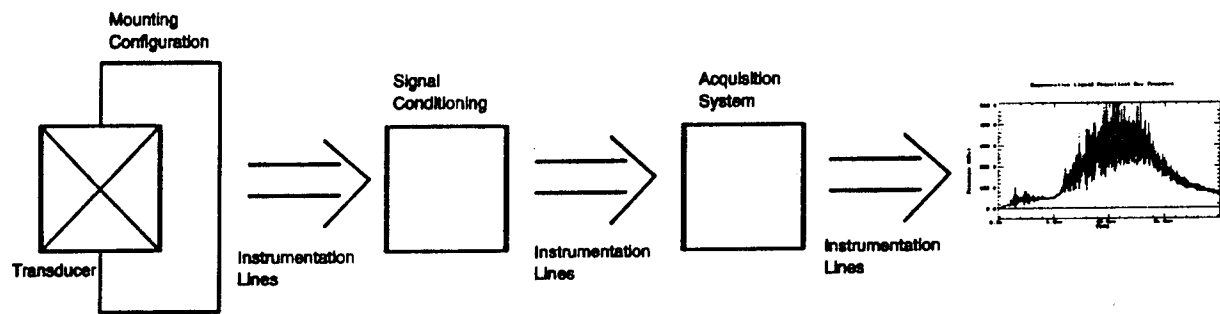
Figure 2. Block diagram of a typical measurement system.

6

The mounting configuration used in implementing the transducer can also play a major role in the validity of the high-frequency measurement. The configuration of traditional two-diameter gauge port cavities, typically filled with grease to protect the transducer from thermal effects, has a major impact on the frequency response of the measurement. It is not known at this time the full extent that gauge port filling materials have on the measurement. The effects of silicone grease and RTV have not been fully investigated.

Other phenomena such as barrel pressure data showing high-frequency oscillations before passage of the projectile, and subsequent exposure to combustion pressure, lead investigators to believe that the gauges are ringing in the high-frequency environment. The difficulty with this is that if the barrel gauge shows a level of oscillations due to gauge vibration phenomena, the question naturally arises as to what contribution this has to the total amplitude of oscillations measured in the combustion chamber or projectile base. Gauges mounted at the end of the muzzle in large-caliber weapons, or used in high-velocity firings, often tend to be destroyed due to a dynamic flexural wave traveling down the tube. In both instances mentioned, it would be advantageous to develop a vibration-insensitive mounting technique to allow meaningful characterization of the combustion environment.

Finally, problems associated with a lack of proper signal conditioning were discussed. A phenomenon known as aliasing was reviewed, which, if not properly accounted for, can severely bias the frequency response of the measurement. Data were recorded with and without an anti-aliasing filter to demonstrate the effects of not filtering the data correctly. The data presented clearly demonstrated the importance of proper signal conditioning in accurately resolving frequencies over the range of interest.

Rosenberger summarized by stating that the measurement techniques used in these highly transient, spectrally rich combustion environments were in need of further review. Consequently this workshop was organized to examine measurement challenges and attempt to gain a community consensus on solutions for making high-fidelity pressure measurements in these environments.

5.1 Oscillatory Pressure Measurements in High-Frequency Environments. It is very important to note here that pressure measurements in high-frequency applications such as RLPGs actually consist of two components; the quasi-steady-state, or mean pressure, and the oscillatory pressure. Figure 3 represents a typical procedure for analyzing these data. The upper left is a plot of raw p-t data. The upper right is a plot of the quasi-steady-state (mean pressure) portion of the data, which is arrived at by performing a

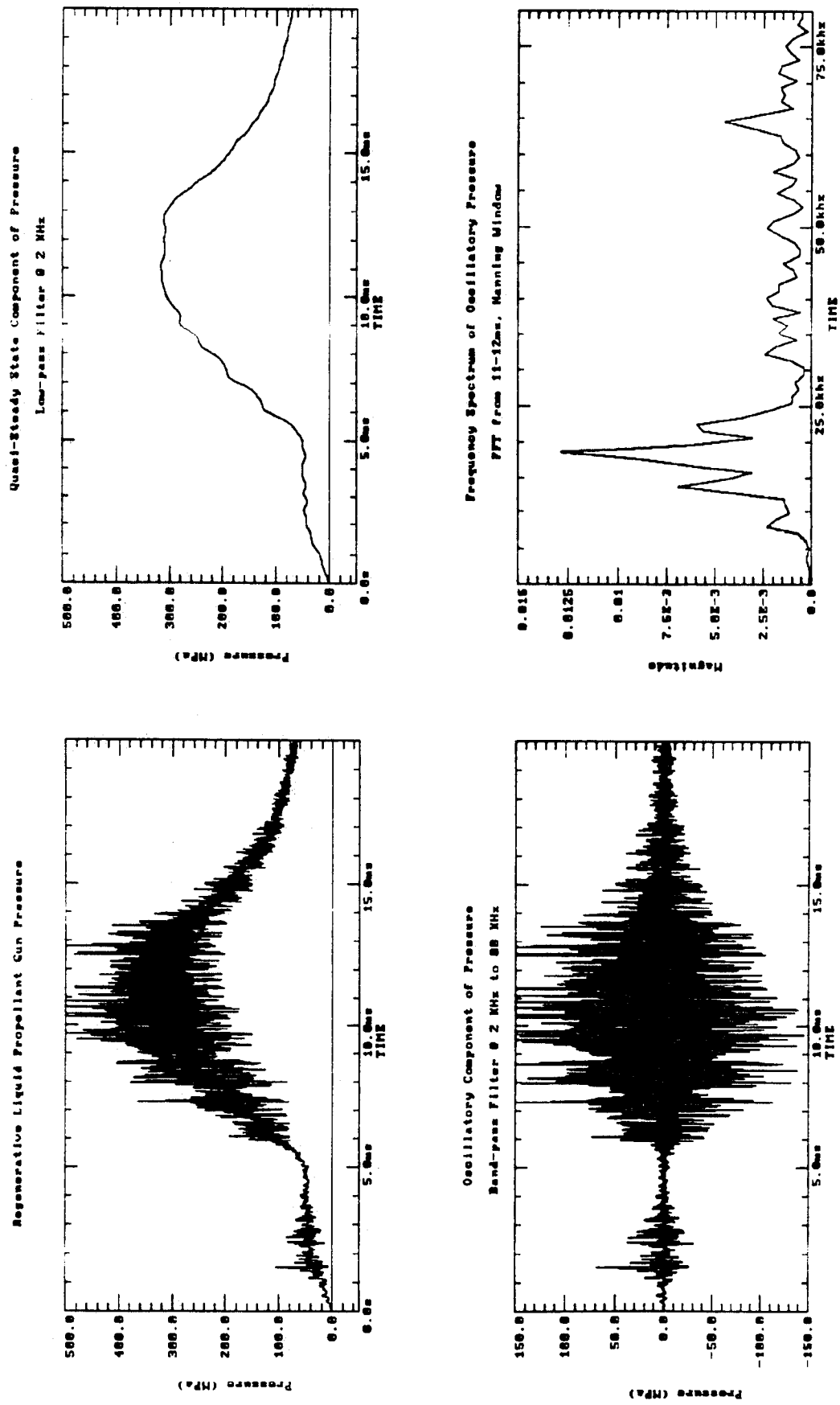# Methodology For Reduction of Pressure-time Data

Figure 3. Typical procedure for analyzing both the quasi-steady-state and oscillatory components of a spectrally rich combustion pressure.

8

low-pass filtering operation at about 2 kHz to remove the high-frequency component. The lower left is a plot of the oscillatory portion of the data which is obtained by performing a band-pass filtering operation between 2 kHz and 80 kHz to remove the quasi-steady-state component. Finally, the lower right is a magnitude vs. frequency plot of the Fast Fourier Transform (FFT) for the oscillatory portion of the data. This frequency spectrum can then be compared to those of pressure measurements at other locations to gain insight as to both the amplitude and energy contained in the oscillatory portion of the p-t data.

To date, most investigators have made use of the standard two-diameter gauge port mounting configuration, filled with grease for thermal protection, in an effort to characterize both the quasi-steady-state portion as well as the oscillatory portion of the combustion pressure. Typically data are taken at several radial locations within a single longitudinal position in an attempt to more accurately characterize the combustion process of the RLPG. Analysis of these data has demonstrated good agreement in the quasi-steady-state portion of the p-t data, but showed considerable variation in terms of the amplitude and frequency response of the oscillatory portion of the data. As it turns out, the data were severely limited in their frequency response due to the configuration of the measurement system.

Data from the SNL liquid injector/combustor were presented by R. Rychnovski as an example of this phenomenon. These data consisted of five pressure measurements in a single longitudinal plane (P31-P35) which measured the same quasi-steady-state pressure, but which exhibited considerably different amplitude and frequency components of the oscillatory pressure. When several of the ports were modified and configured as single-diameter through ports, the large variation in both amplitude and frequency response was eliminated between the data taken with the single-diameter ports.

Dr. G. A. Benedetti of SNL offered both a theoretical and an experimental explanation of this phenomenon. In order to make a good measurement, the system requires a flat response ($P_{out}/P_{in}=1$) over the range of frequencies of interest associated with the input signal. This implies that the natural frequency of the gauge port cavity and transducer must be significantly higher than the highest frequency of interest in the input signal (i.e., $f_{nat\ cavity} \geq 5\ f_{input\ signal}$). The steady-state pressure response spectrum for a two-diameter gauge cavity is shown in Figure 4.

ω is the frequency of pressure oscillation at the gun tube wall, and ω_n is the first undamped natural circular frequency for the cavity. As one can see, at about 20% of the resonant frequency, the magnitude of P_{out}/P_{in} begins to be amplified. At frequencies above 20% and near the resonant frequency, the input

9

signal will be severely amplified. At frequencies significantly higher than the natural frequency, the input signal will be severely attenuated. As one would expect, this would have a very profound effect on the quality of the data if the resonant frequency of the transducer cavity is low with respect to the range of input frequencies of interest.

An acoustical analysis of the cavity results in the expression for the first natural frequency for the transducer cavity, shown in Figure 5.
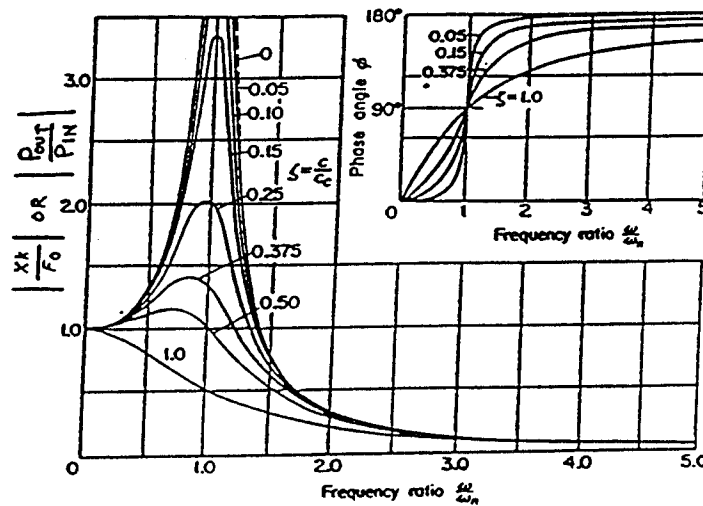

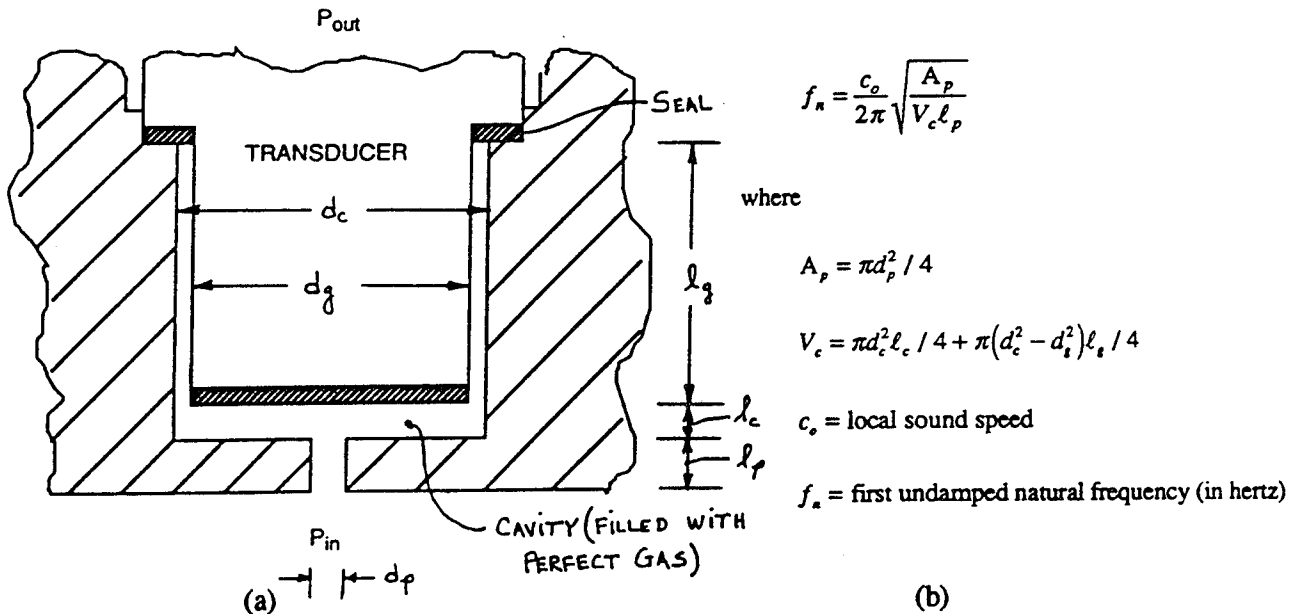Figure 4. Steady-state pressure response spectrum for a two-diameter gauge cavity.

$$f_n = \frac{c_o}{2\pi}\sqrt{\frac{A_p}{V_c \ell_p}}$$

where

$$A_p = \pi d_p^2 / 4$$

$$V_c = \pi d_c^2 \ell_c / 4 + \pi(d_c^2 - d_s^2)\ell_s / 4$$

c_o = local sound speed

f_n = first undamped natural frequency (in hertz)

(a)   (b)

Figure 5. (a) A two-diameter gauge cavity and (b) an expression for the first natural frequency of a two-diameter gauge cavity.

10

The gauge cavity resonant frequency of typical two-diameter gauge ports which are within specification range from 30–40 kHz. It is important to note that the cavity dimensions can vary due to tolerances, machining errors, and installation procedures. If one assumes cavity-resonant frequencies of 30–40 kHz, then the data acquired using these ports are "flat" to only 6–8 kHz. At frequencies above 6–8 kHz, the data will be biased significantly. Benedetti presented data from acoustic measurements which support the theoretical analysis outlined above. In addition, a comparison of nonacoustical data acquired in the SNL liquid injector/combustor was presented which also supported this assertion (Benedetti 1993).

James DeSpirito of the ARL presented data taken in an RLPG which also supported the assertion made above. Results showed that both two-diameter and single-diameter gauge port cavities without grease follow the acoustical analysis. In addition, the two-diameter cavity limits the frequency response of the measurement to a few kilohertz. Perhaps equally important, the effects of the use of silicone grease in the two-diameter ports were studied. It was found that when silicone grease was used in the two-diameter port, the data did not follow the acoustical analysis. The reason for this is because the grease that is initially packed in the gauge cavity is not present after testing. At some point during the interior ballistic cycle, the grease is removed from the cavity and the local sound speed in the cavity changes. Consequently the acoustic analysis does not hold.

To demonstrate that the measurement of high-frequency pressure oscillations was not unique to the RLPG community, Mr. David Kruczynski of the ARL gave an overview of pressure measurements taken in the 120-mm in-bore ramjet accelerator. He showed that the combustion environment in this propulsion concept is much like that of the RLPG. Pressure measurements taken with two-diameter gauge port configurations were shown to severely limit the frequency response of the data when compared to those of single-diameter gauge ports.
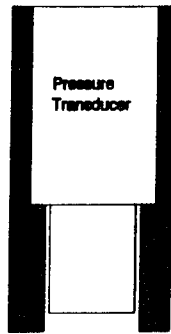
Based upon the data acquired at SNL and supported by studies at the ARL, Benedetti put forward a procedure for characterizing both the quasi-steady-state and the oscillatory portions of the p-t data. The procedure is outlined in Figure 6.

It was the consensus of the workshop participants that this procedure would greatly improve the characterization of the oscillatory portion of the combustion environment. In most cases, the quasi-steady-state portion of the measurement is of primary interest. However, when the effects of the high-frequency

11
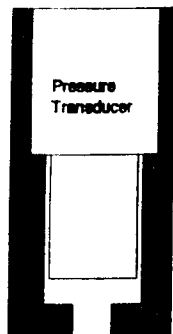
Two-diameter port	One-diameter port
- **Quasi-steady-state**	- **Oscillatory**
- 0.090" offset	- $\leq$ 0.030" offset
- Mechanically stable gage	- Well characterized gage
- Grease for thermal protection	- No grease (likely extreme thermal drift)

Recommended procedure to be used when oscillations must be studied:

- Use both two-diameter ports with grease and one-diameter ports without grease
- Use low-pass filtered pressure-time history from two-diameter port to define the "quasi-steady-state", or mean pressure
- Use pressure-time from the one-diameter port, with mean pressure (with likely thermal drift effects) removed, to define the oscillatory pressure

Figure 6. Procedure for measuring both quasi-steady-state and oscillatory components of a spectrally rich combustion pressure.

content of the combustion process must be studied, this procedure should be implemented using the single-diameter gauge port configuration. The pressure gauges should be mounted ≤ 0.030 in from the combustion gases without grease in order to resolve the input frequencies of interest (near-DC to 80 kHz). It is worth noting here that the participants felt that a minimum of single-diameter ports should be implemented due to the probability that the gauge may need to be replaced after every test due to extreme thermal and vibrational shock loading. Obviously this procedure could prove to be quite expensive, but at this time it is the only methodology known to successfully characterize the high-frequency combustion environment.

5.2 Alternate Pressure Transducers. Alternate pressure transducers have been developed that are designed to survive the severe thermal and oscillatory environment. Mr. Welton "Red" Phillips has designed, built, and tested a series of tourmaline pressure transducers which have proven to be quite reliable for characterizing the quasi-steady-state pressure under severe conditions. His presentation outlined the highlights of the design which makes use of tourmaline, a pressure-sensitive crystal similar to quartz, packaged in a housing very much like that of other high-pressure ballistic transducers. These gauges have been used routinely to measure quasi-steady-state combustion pressure in conventional interior ballistic testing for several years and have been demonstrated to compare quite well with other high-pressure piezoelectric pressure transducers.

12

Two design modifications were made to the transducers specifically for the severe oscillatory combustion environment. To eliminate the problem of the high mechanical failure rate of other ballistic transducers, the gauge was made to have a larger diameter (14 mm, 0.551 in) than traditional high-pressure ballistic transducers (0.375 in). The increased diameter allows greater torque to be used when installing the transducers. Traditional transducers are only torqued to 20–25 ft-lbs whereas the tourmaline transducer can be torqued to 90 ft-lbs, giving much greater mechanical stability. In addition to the larger diameter, there is also a built-in heat shield which goes a long way to prevent adverse thermal effects.

There are however, several unknowns that prohibit the use of this transducer for studying the oscillatory portion of the combustion pressure. Mr. Phillips has not quantified the transducers' resonant frequency, the rise time, nor the effects of the thermal heat shield on the high-frequency data. Consequently, the workshop participants felt that further laboratory testing should be completed before information could be gained concerning the oscillatory portion of data acquired using these transducers. It cannot be overemphasized that the transducers perform extremely well in this environment for characterizing the quasi-steady-state portion of the combustion pressure.

5.3 Alternate Pressure Measurement Techniques. Alternate pressure measurement techniques were also presented at the workshop. Mr. Jody Wormhoudt of Aerodyne Research, Inc. presented work completed under a Small Business Innovative Research (SBIR) contract for the U.S. Navy which entailed the design, manufacture, and test of a fiber optic pressure transducer for underwater blast testing. The presentation outlined the approach of using the fluorescence of ruby in conjunction with fiber optic technology to monitor detonation blast pressures to 250 kbar. The advantages of the technique were primarily that it was insensitive to electromagnetic effects because of the optical link; it had very fast response times to 0.1 µs; and the fact that it implemented flashlamp-excited plastic optical fiber containing fluorescent dye, and ruby crystals, all of which are relatively inexpensive and easily obtained (bulk cost similar to piezoelectric transducers). The disadvantages which currently prohibit its use in interior ballistic testing are its sensitivity to thermal effects, the insensitivity of the technique to pressure levels of interest, and the gauge's low resonant frequency. However, modifications to the technique were proposed which would allow the use of this technique in interior ballistic testing. The development time and costs were not estimated.

The CSTA, of the Test and Evaluation Command (TECOM) of the U.S. Army, has been actively pursuing fiber optic pressure transducers for electrothermal/electromagnetic gun propulsion application

13

because of their insensitivity to electromagnetic interference. To this end, they have initiated several SBIR contracts to various companies to explore the feasibility and implementation of fiber optic technology in the measurement of interior ballistic combustion pressure. The CSTA point of contact, Mr. W. Scott Walton, was not able to attend the workshop; however, a survey of the promising SBIR programs was presented by the workshop chairman after close consultation with Mr. Walton.

The presentation on fiber optic pressure transducers was prefaced with Mr. Rosenberger stating that the interior ballistic community has not heard much in the way of fiber optic pressure measurement technology because it is a relatively immature, rapidly changing technology. There has been a great deal of work done in the area, but not much has been written in the U.S. because it has been held proprietary. Three techniques were discussed in the presentation. The most promising fiber optic pressure measurement technique was patented by Quest Inc. and is based on light intensity reduction due to diaphragm displacement (U.S. patent 4,158,310). It is packaged in a transducer that has the form function of a Kistler 6211 high-pressure ballistic transducer. Fibers which include both illuminating and receiving fibers are bundled together and placed in close proximity to a reflective diaphragm. The diaphragm is exposed directly to the combustion gases. As the diaphragm flexes under pressure, the reflected light intensity changes in a manner proportional to the input pressure. The reflected light is sensed by a remotely located photodetector via the receiving fiber optic link. This transducer was statically demonstrated to 945 MPa and dynamically demonstrated using a pressure pulse generator to 690 MPa. Some of the disadvantages of this technique are its low resonant frequency (160 kHz) and susceptibility to mechanical failure. Modifications to eliminate these problems are being implemented under a Phase II SBIR, and the transducer should be ready for testing at CSTA/ARL during the spring of 1994.

Although fiber optic pressure measurement technology appears to be too immature for characterizing the oscillatory portion of the interior ballistic combustion pressure immediately, the technology is rapidly maturing and the consensus among the workshop participants was that the technology was worth exploring further.

6. CONCLUSIONS AND RECOMMENDATIONS

The attendees were in agreement that the pressure measurement techniques presently being used to characterize the transient, high-frequency combustion environment in several of the advanced propulsion technologies are inadequate and consequently of serious technical concern. The specific issues of

paramount concern were the inappropriateness of using two-diameter pressure transducer ports to characterize the oscillatory nature of the combustion pressure in RLPGs and in-bore ramjets, and the practice of operating at the limit of present pressure transducer technology specifications.

Theoretical and experimental data were presented which demonstrate that two-diameter pressure transducer mounting configurations filled with grease to eliminate thermal effects have the effect of limiting the frequency response of the measurement to 6–8 kHz. The portion of the data with frequency content near the resonant frequency of the cavity is amplified, while the portions of the data with frequency content significantly above the resonant frequency are severely attenuated. Consequently the oscillatory portion of the pressure database that has been accumulated to date is biased above 6–8 kHz. A procedure was put forward that would allow one to accurately measure the quasi-steady-state, or mean pressure, as well as the oscillatory portion of the combustion pressure. The consensus of the workshop participants was that this procedure would provide an accurate characterization of both portions of the pressure data. There was also some discussion as to whether a "correction factor" could be applied to data acquired using a two-diameter pressure port to account for the frequency limitations at the higher frequencies. Consensus could not be reached as to whether or not it would be possible to accurately apply this "correction factor," however, consensus was reached that the concept deserved further investigation.

The tourmaline pressure transducer which implements a larger diameter and built-in thermal protection is viewed by the workshop participants as a means of decreasing the failure rate of the pressure transducers in this environment, but should only be used for quasi-steady-state measurements due to the unknown technical specifications concerning the transducer's resonant frequency, rise time, and the effects of the thermal protection on the oscillatory measurement. In addition, fiber optic pressure measurement techniques were presented which seem to have possible application to the transient, high-frequency environment of RLPGs and in-bore ramjets; as well as to the high electrical noise environment of electromagnetic and electrothermal guns. It was the consensus of the participants that more basic research was needed to explore alternative pressure measurement techniques and to attempt to quantify the technical specifications of transducers currently being used to characterize highly transient, spectrally rich combustion environments.

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7. REFERENCES

Benedetti, G. A. "Dynamic Response of a Transducer Mounted at One End of an Acoustical Cavity." SAND92-8003, Sandia National Laboratories, Livermore, CA, April 1993.
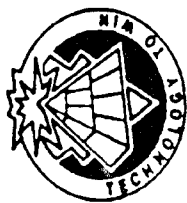
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APPENDIX A:

PRESENTATION - "MEASUREMENT TECHNIQUES IN HIGHLY TRANSIENT,
SPECTRALLY RICH COMBUSTION ENVIRONMENTS:
WELCOME, WORKSHOP MOTIVATION AND OBJECTIVES"

*This Appendix is presented in its original form without
editorial changes or comments.*

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Weapons Technology Directorate

ARMY RESEARCH LABORATORY

30th JANNAF Combustion Subcommittee Meeting Workshop on

MEASUREMENT TECHNIQUES IN HIGHLY-TRANSIENT, SPECTRALLY-RICH, COMBUSTION ENVIRONMENTS

Todd E. Rosenberger

Weapons Technology Directorate

U.S. Army Research Laboratory

Aberdeen Proving Ground, Md 21005-5066

Phone: 410-278-6136 FAX: 410-278-6174

Monterey, California

19 November, 1993

21

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Measurement Techniques in Highly-Transient, Spectrally-Rich, Combustion Environments

Overview of Presentation

- □ Motivation for the Workshop

- □ Objectives of the Workshop

- □ Survey Measurement Challenges/Problems

Motivation for the Workshop

☐ **Continuous measurement of ballistic performance during the interior ballistic cycle of cannon-launched projectiles has traditionally been used to evaluate:**

☐ **Propelling Gas Pressure**

☐ **Projectile Acceleration**

☐ **Projectile-bore Interactions**

☐ **Torsional Impulse**

☐ **System Response to Engraving**

☐ **These phenomena have been traditionally characterized by relatively low frequency transient behavior**

24

Motivation for the Workshop

Chamber pressure and projectile base pressure from a solid propellant system

Motivation for the Workshop
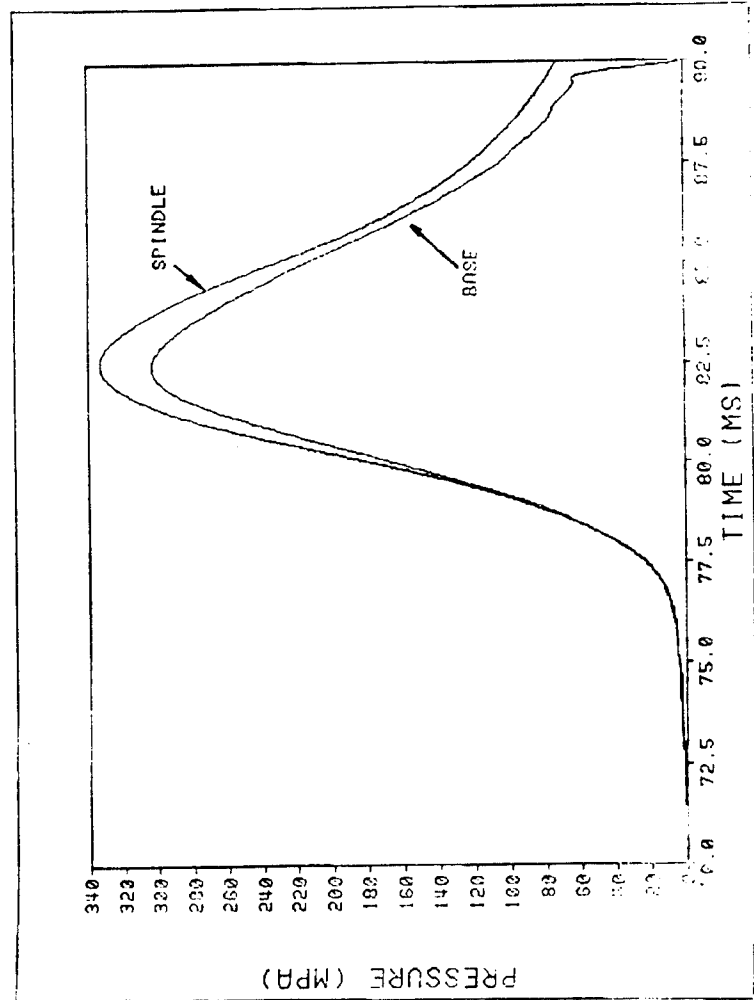
☐ More recently, interest has turned to characterizing the combustion environment in advanced propulsion systems such as:

  ☐ Regenerative Liquid Propellant Guns

  ☐ Electric/Electrothermal-Chemical Guns

  ☐ Inbore Ramjets

  ☐ Conventional Hypervelocity Guns

☐ Interior ballistic phenomena in these systems have been characterized by much higher frequency transient behavior

Motivation for the Workshop

Inbore Ramjet

Pressure (MPa)

150.0 100.0 50.0 0.0 -50.0

25.0ms   30.0ms   35.0ms
TIME

Regenerative Liquid Propellant Gun

Pressure (MPa)

250.0 200.0 150.0 100.0 50.0 0.0 -50.0

5.0ms   10.0ms   15.0ms
TIME

Electrothermal-Chemical Gun

27
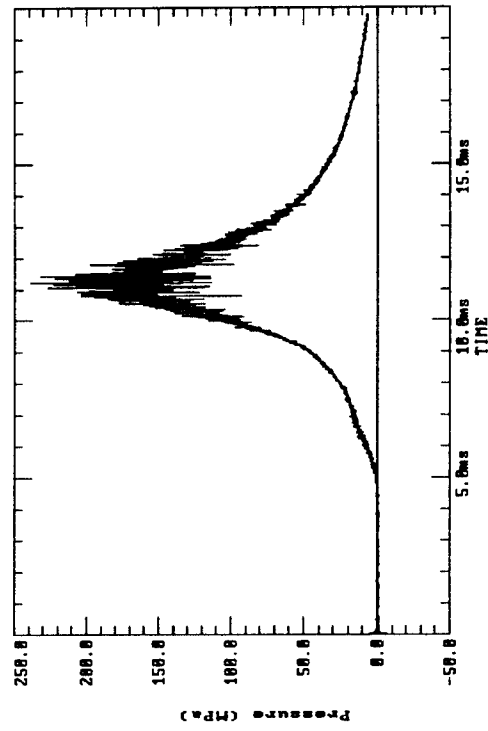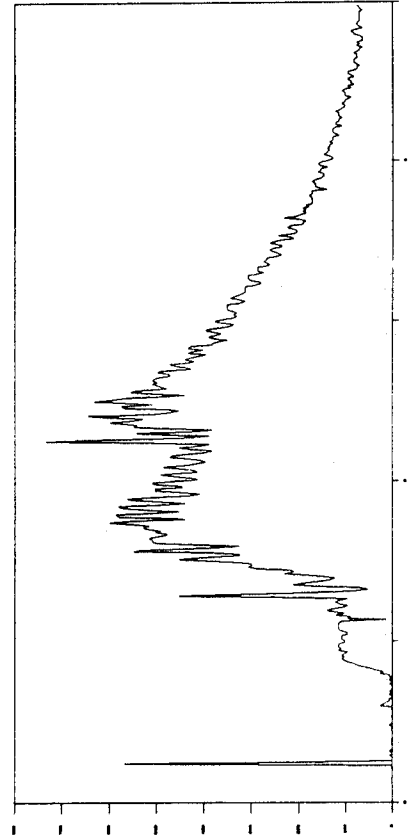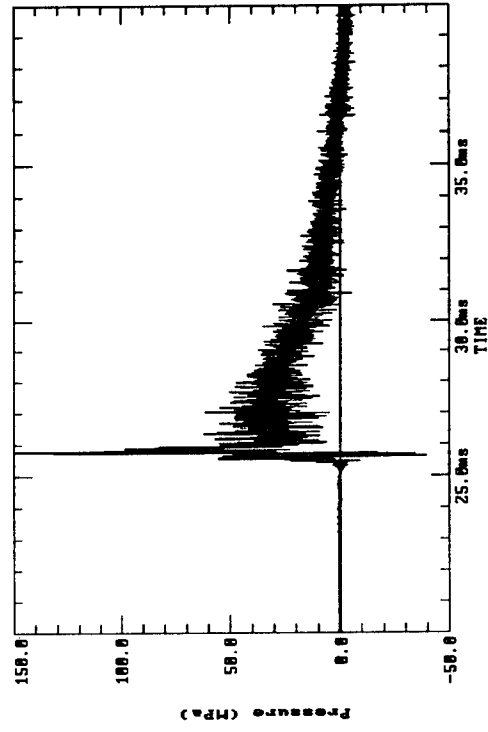
Motivation for the Workshop

☐ **Data such as these are presently being used throughout the advanced propulsion community to:**

☐ **Evaluate propulsion system concept feasability**

☐ **Develop theoretical models**

☐ **Draw conclusions concerning system safety**
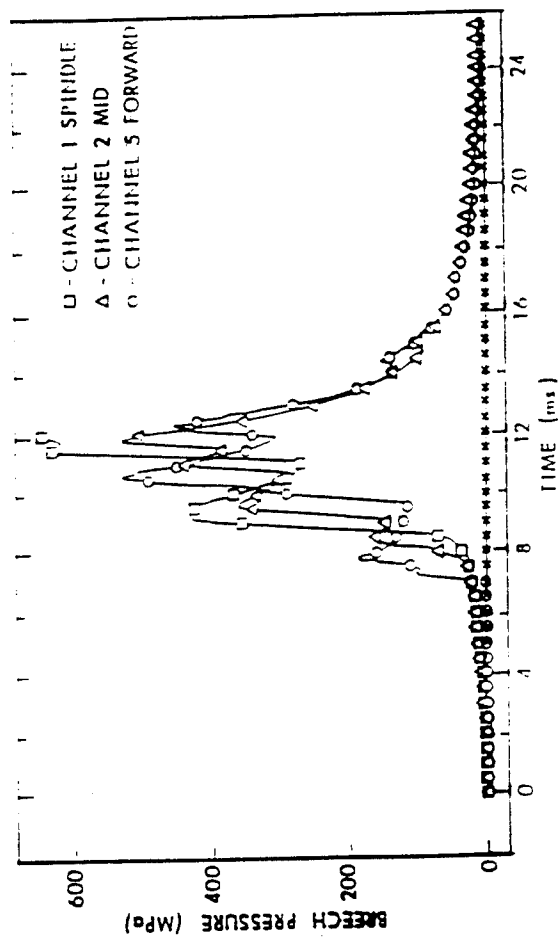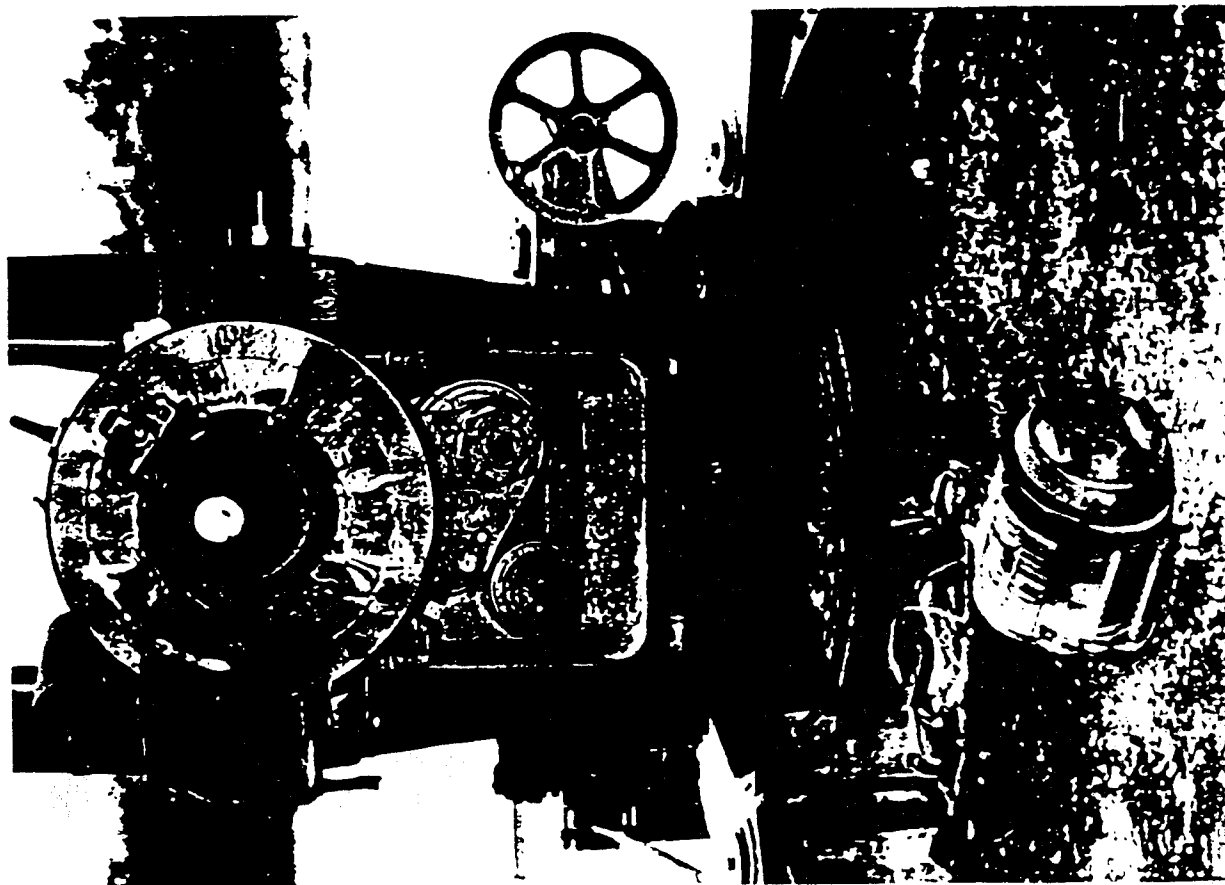
Motivation for the Workshop

What will be the effects of the pressure oscillations on system integrity and safety?

UNKNOWN IMPACT!
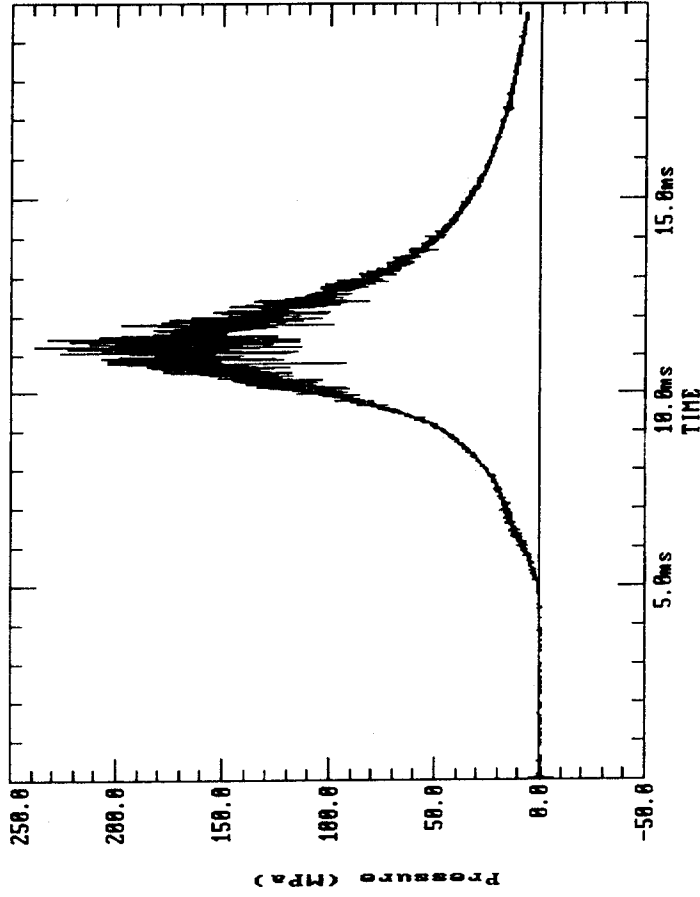
Motivation for the Workshop

□ **Are these data an accurate description of the actual physical processes involved?**

□ **Questions have been put forward concerning the adequacy of measurement techniques used to quantify the combustion environments in these advanced propulsion systems**

□ **General consensus throughout the community is that some of the measurement techniques used to characterize traditional propulsion systems are inadequate for characterizing the "Highly-transient, Spectrally-rich, Combustion Environments" associated with emerging propulsion technologies**

Workshop needed to address these measurement challenges/problems

31

Measurement Techniques in Highly-Transient, Spectrally-Rich, Combustion Environments

Workshop Objectives

□ Outline measurement challenges and problems associated with "Highly-transient, Spectrally-rich, Combustion Environments"

□ Survey measurement techniques appropriate for accurately characterizing these combustion environments

□ Recommend future measurement technology research areas

32

Measurement Techniques in Highly-Transient, Spectrally-Rich, Combustion Environments

Survey of Measurement Challenges/Problems

Basic block diagram of "measurement system"
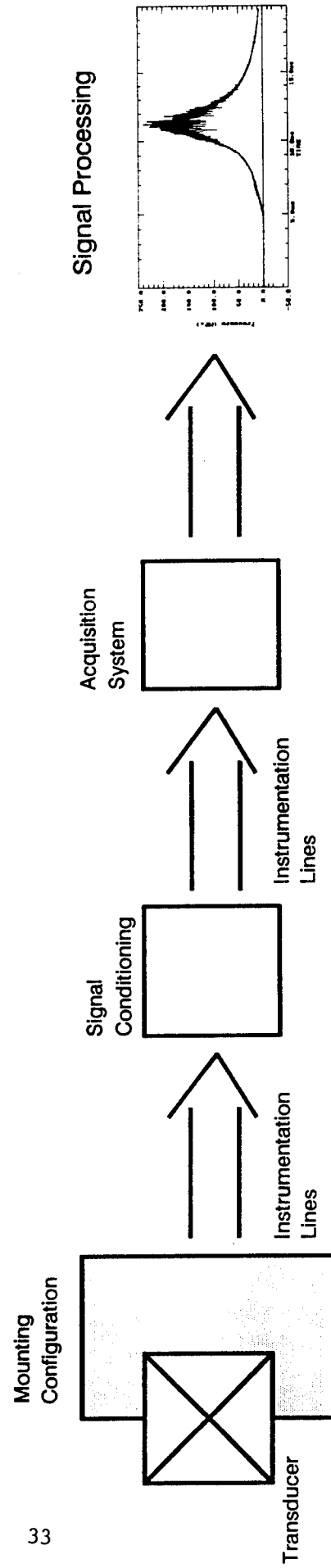
Problems Associated With Transducers

Vender specifications generally accepted in conventional testing

- shock/vibration sensitivity

- rise time response

- acceleration sensitivity

How well do specifications hold up in high frequency environment?

34

Problems Associated With Transducers

Acceleration sensitivity of pressure transducer for instrumented projectile tests

- ☐ **PCB 109A12 piezoelectric pressure transducer**
- ☐ **Acceleration sensitivity specified as 0.004 psi/g**
- ☐ **Vender tested to few hundred g's**
- ☐ **Is the acceleration sensitivity linear?**
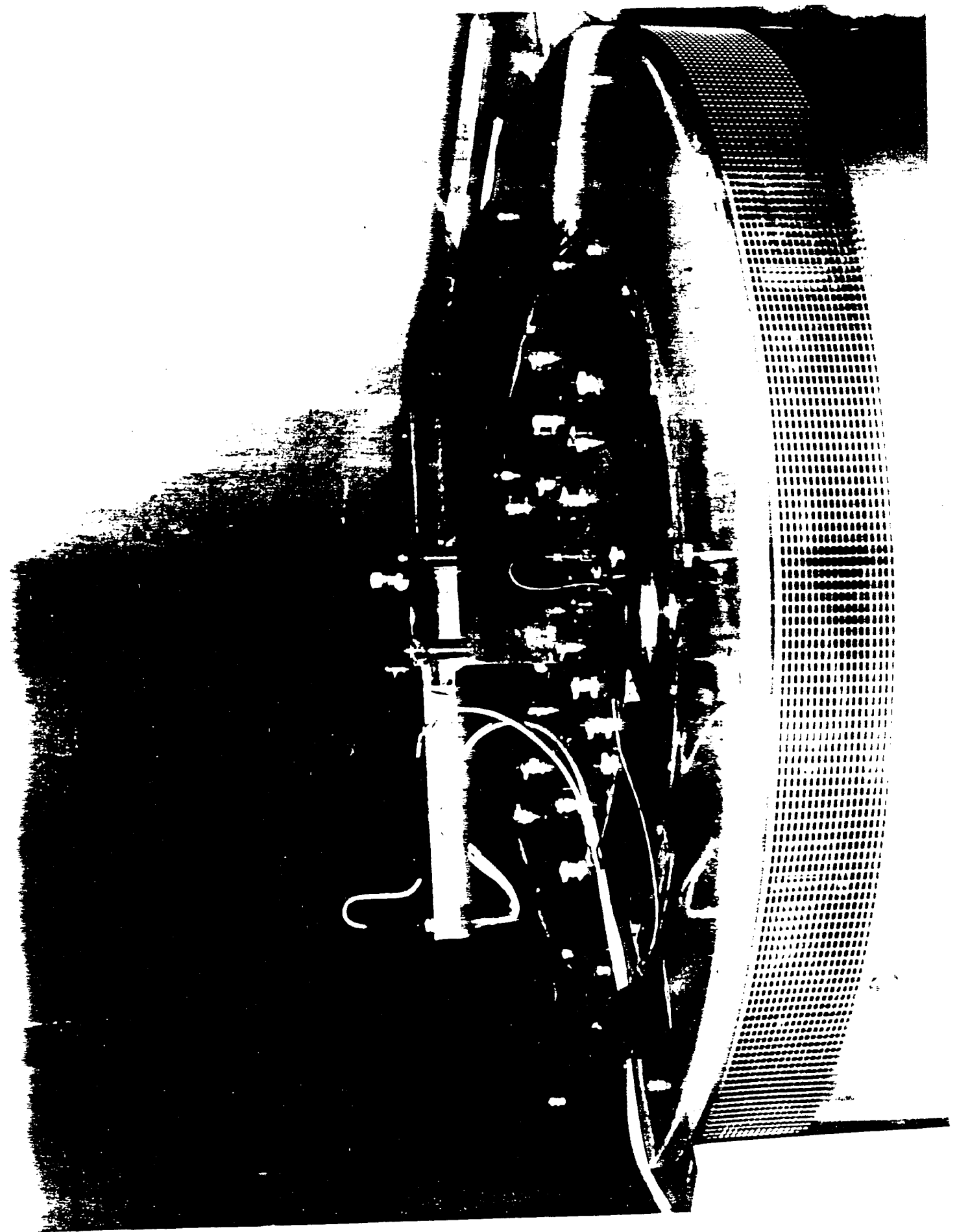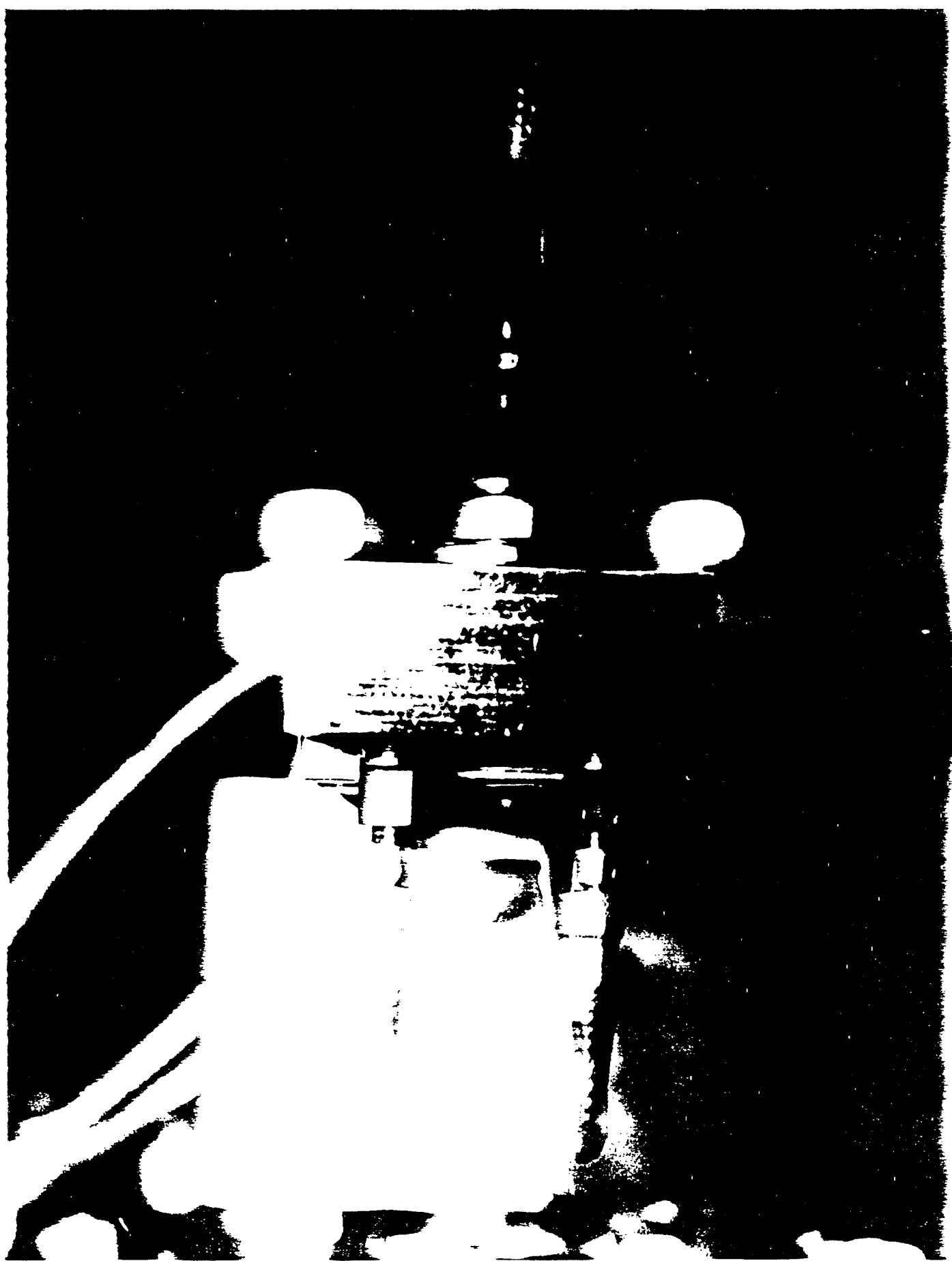
RECENT PRESSURE TRANSDUCER TEST

Applied Acceleration

G's vs Time
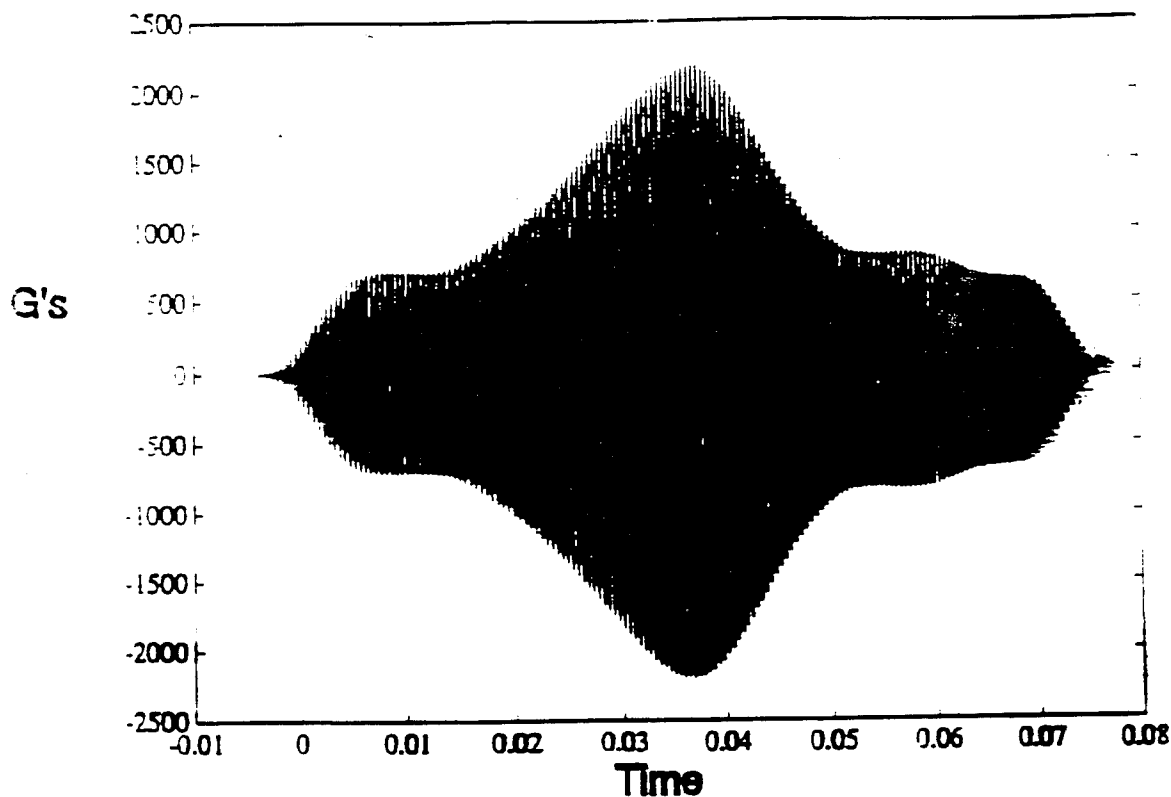
PCB Specimen Response

PSI vs Time
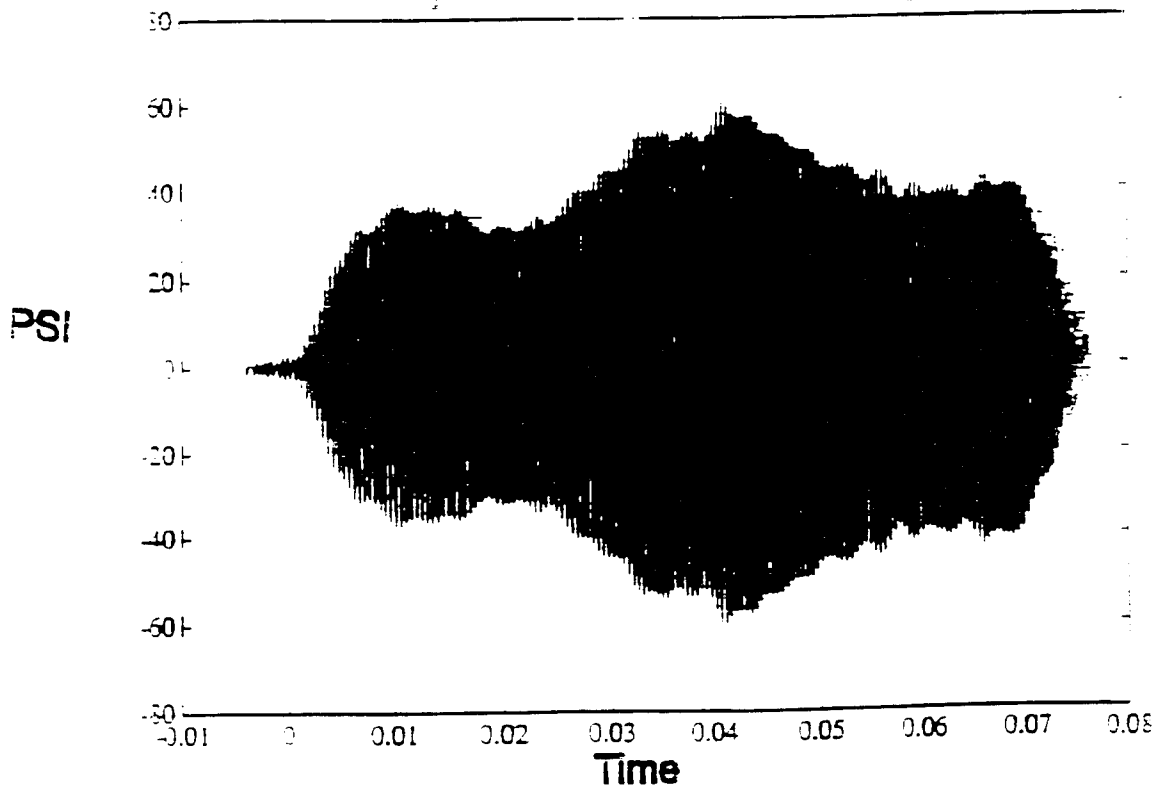
RECENT PRESSURE TRANSDUCER TEST

Acceleration Amplitude
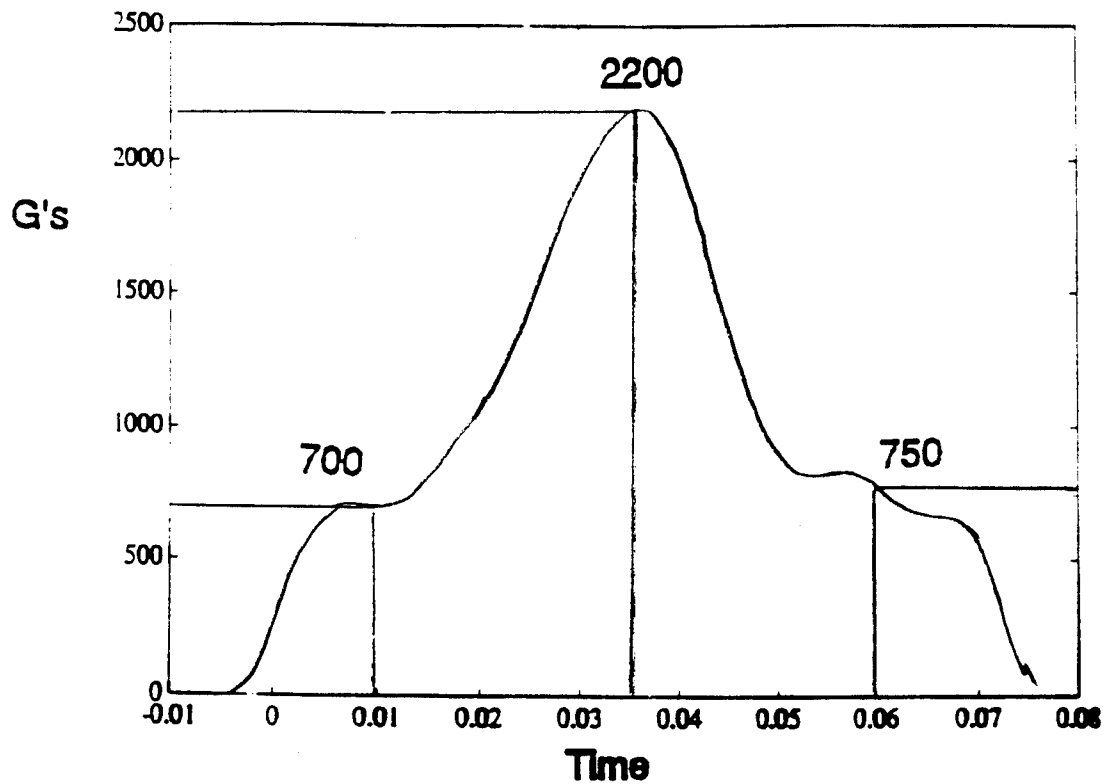
Response Amplitude
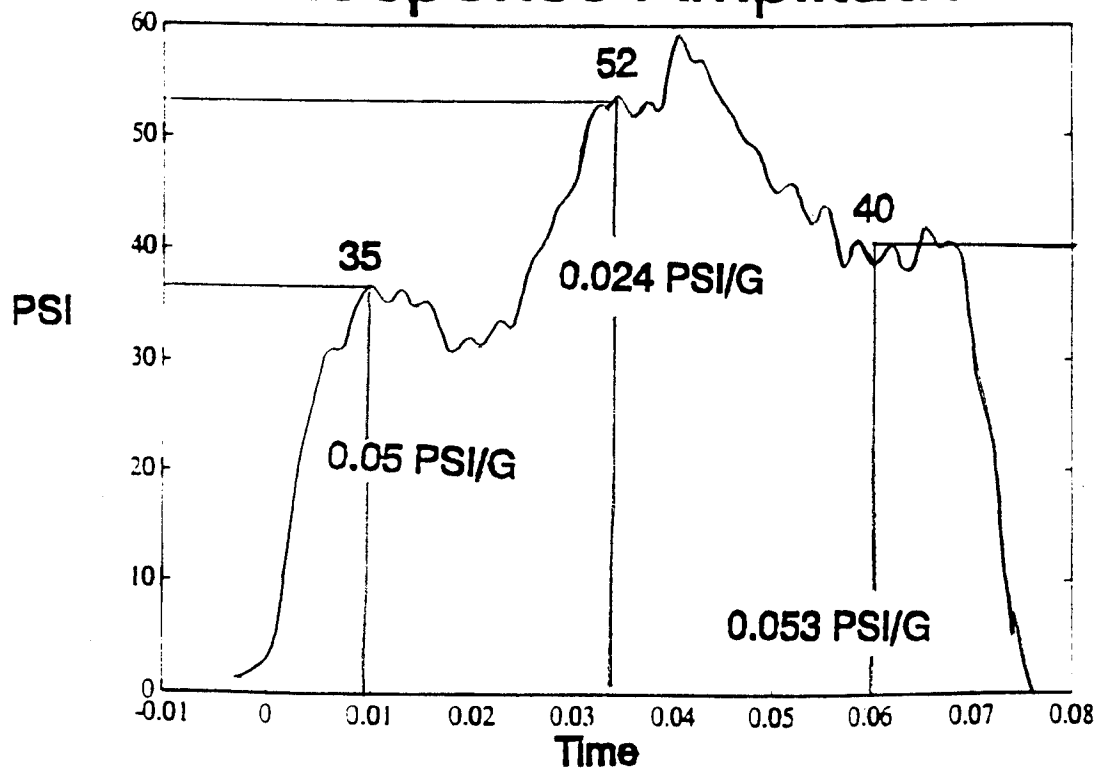
Problems Associated With Transducers

- Several different PCB119A12s tested - averaged 0.07 psi/g

- Tested alternative transducers - Tourmaline (W. Phillips)

  - E30MP - average 0.011 psi/g (2)

  - E30MT3 - average 0.020 psi/g (3)

- Conclusion: only a few percent error if assume this sensitivity at peak acceleration (10-30 kg's), however, have not developed laboratory test to determine sensitivity at actual gun acceleration levels

Problems Associated With Transducers

☐ **Integrity of transducers in high frequency environment**
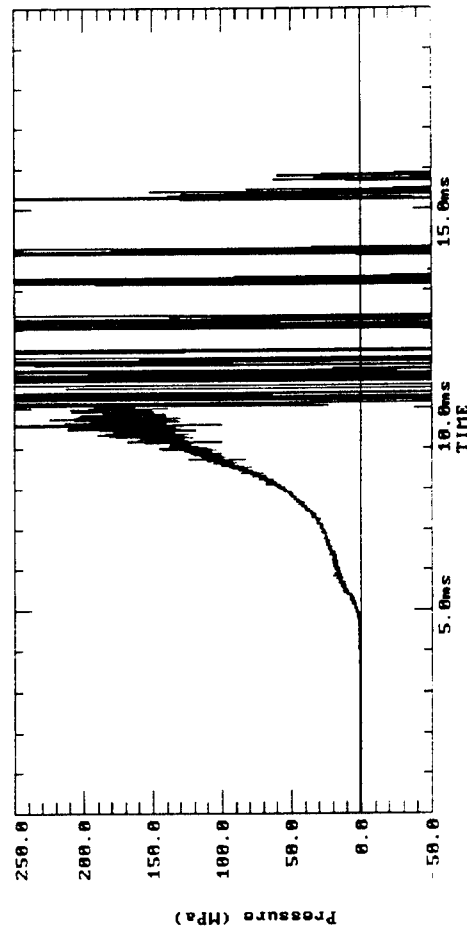
Chamber Pressure
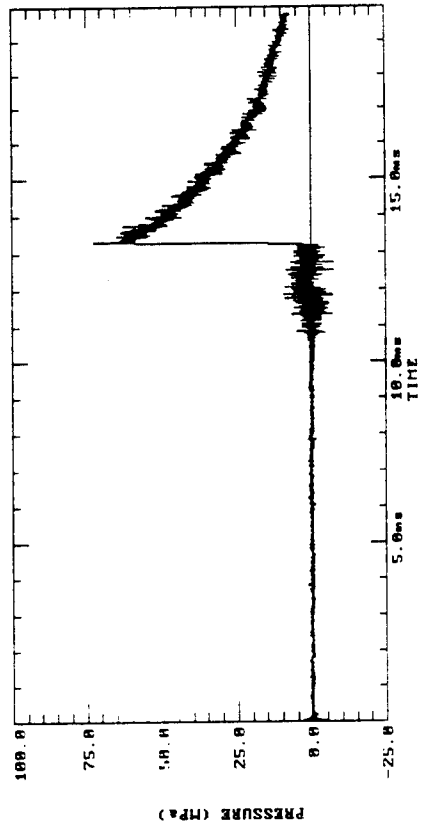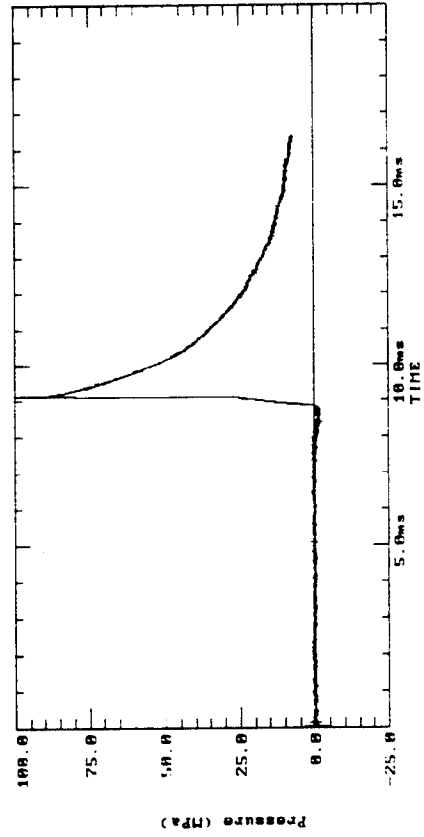

Projectile Base Pressure

41
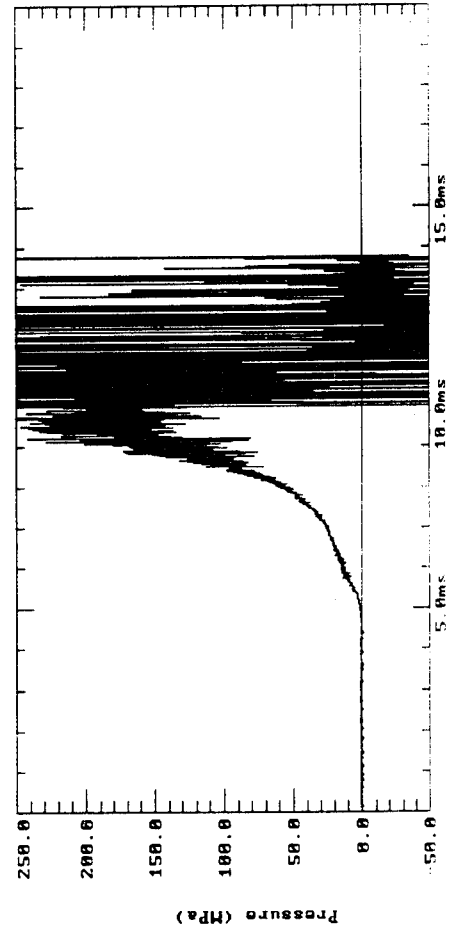
Problems Associated With Mounting Configuration

☐ **Effects of gage cavity configuration, filling materials, and temperature on both amplitude and frequency response**
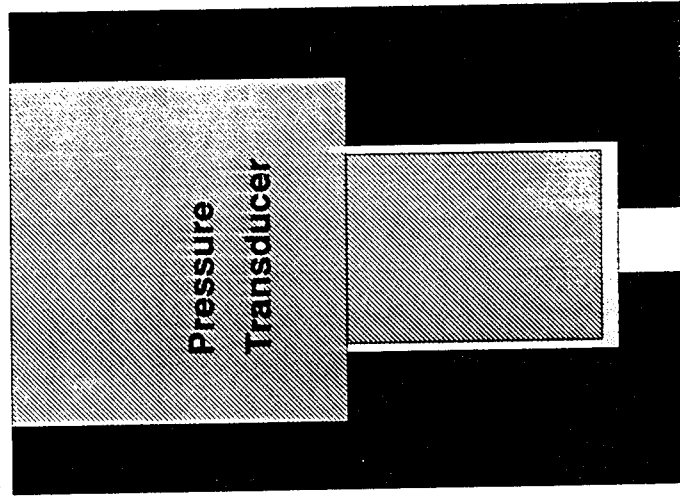
Pressure Transducer

Problems Associated With Mounting Configuration/Transducer

☐ **Barrel mounted transducers ringing?**

43

Problems Associated With Mounting Configuration/Transducer

☐ Barrel mounted transducers failing, expecially at muzzle and at high projectile velocities
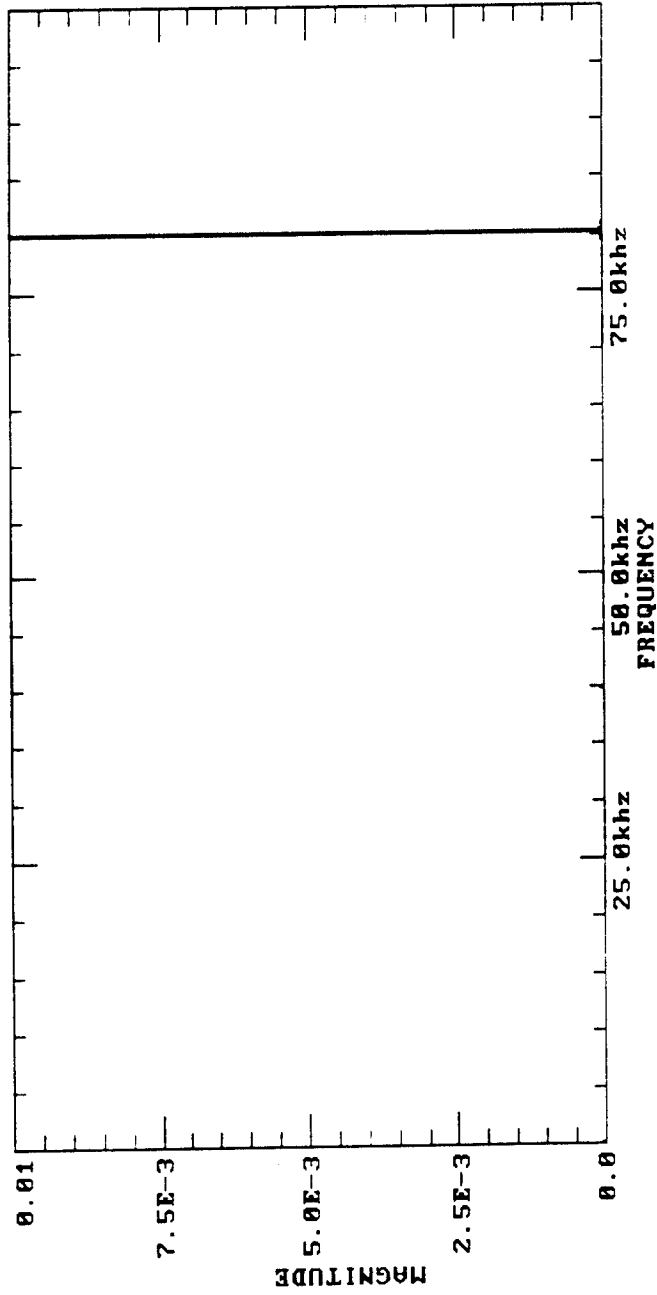
☐ Dynamic flexural wave propagating down tube

Problems Associated With Signal Conditioning/Acquisition System

☐ **Aliasing can severly bias the frequency spectrum of oscillatory data**
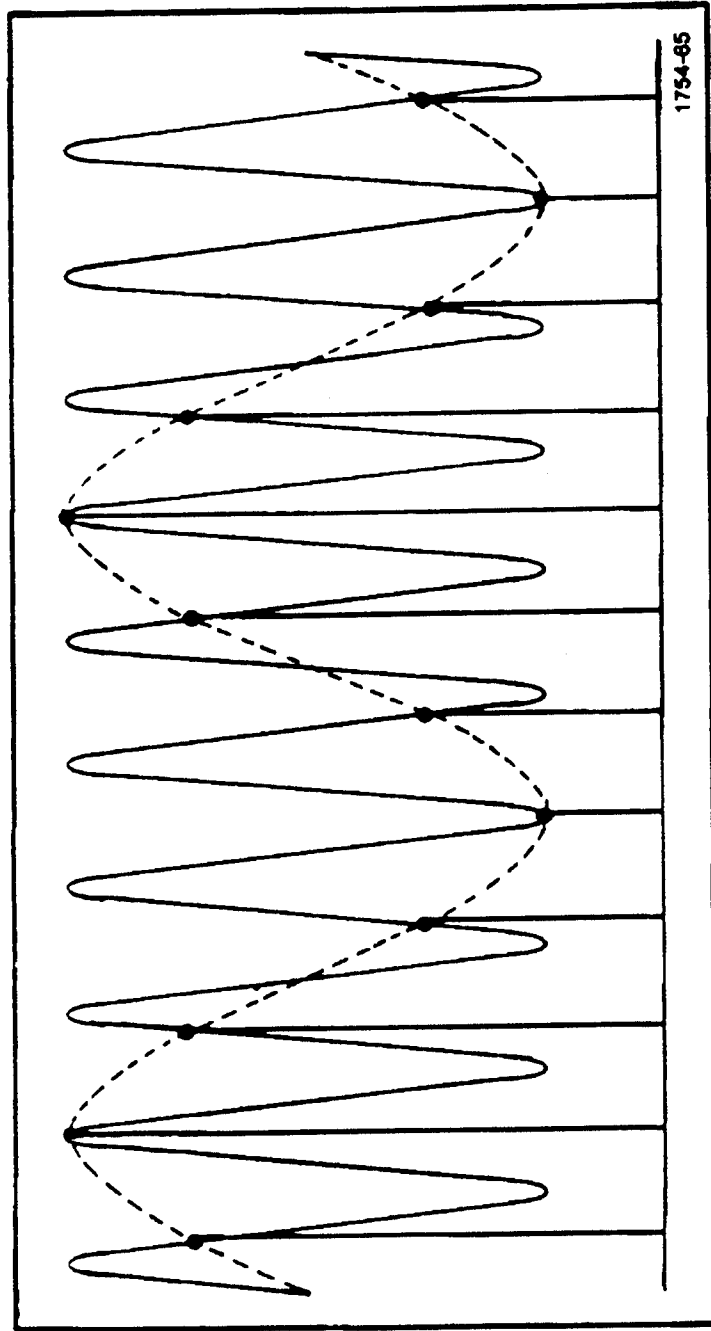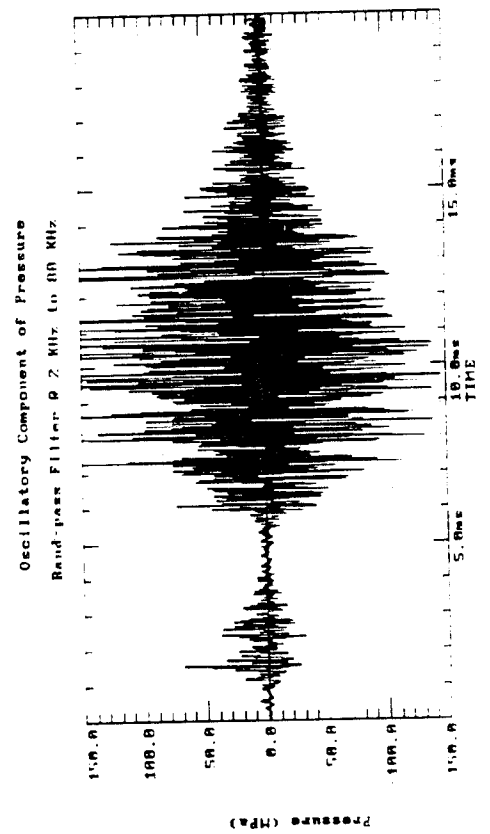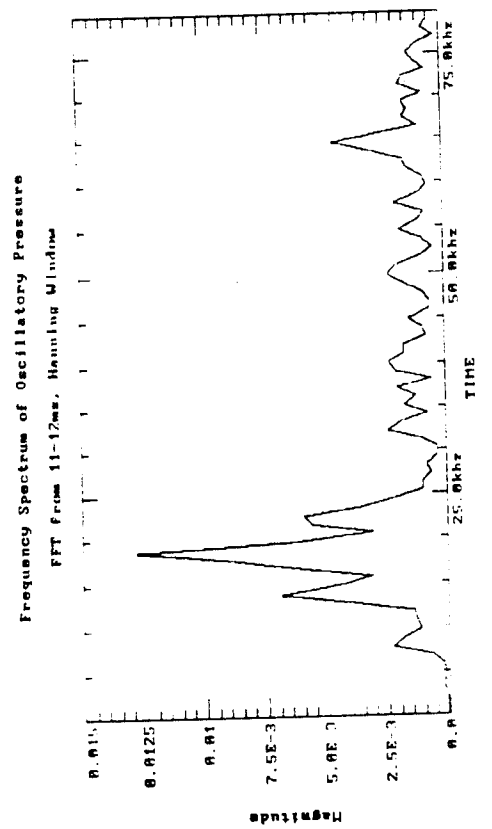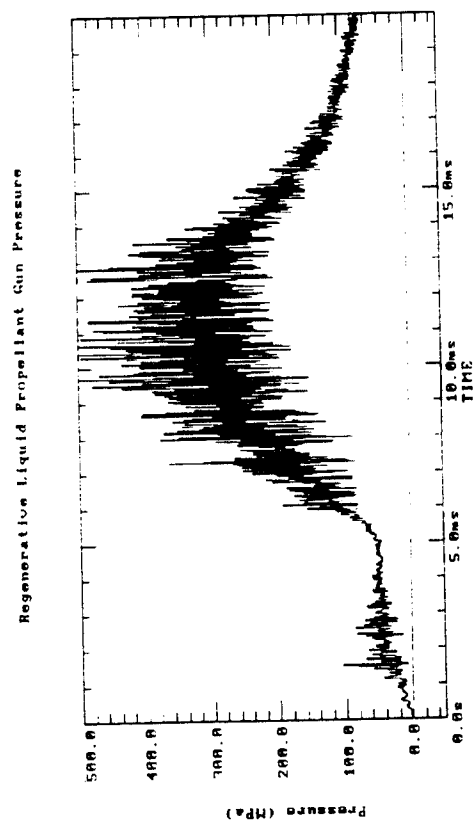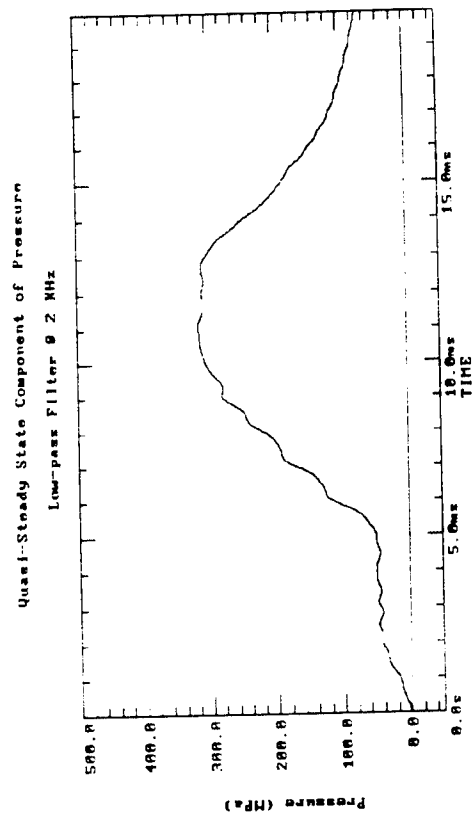
Problems Associated With Signal Conditioning/Acquisition System

☐ Aliasing is the process of higher frequency spectral components folding over into the lower frequency components of the spectrum


FFT of a 120 kHz Sinusoid Sampled at 200kHz

Methodology For Reduction of Pressure-time Data

Regeneration Liquid Propellant Gun Pressure

Quasi-Steady State Component of Pressure
Low-pass Filter @ 2 KHz

Oscillatory Component of Pressure
Band-pass Filter @ 2 KHz to 80 KHz

Frequency Spectrum of Oscillatory Pressure
FFT from 11-17ms, Hanning Window

47

Problems Associated With Signal Conditioning/Acquisition System

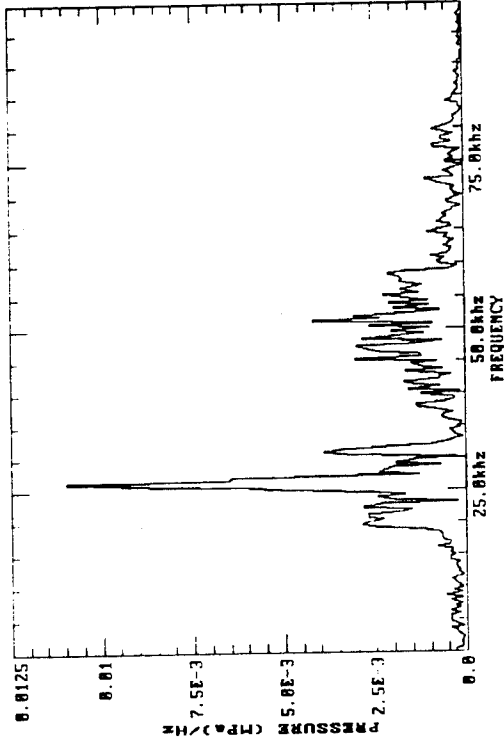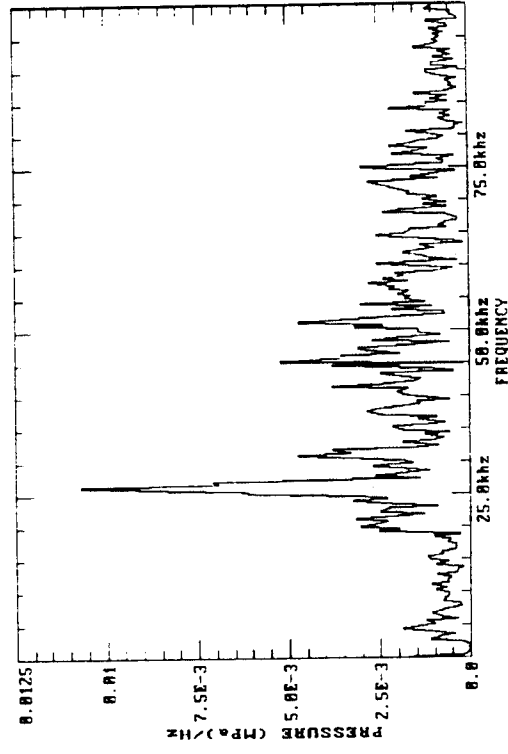## Chamber pressure sampled at 500kHz and corresponding FFT

48
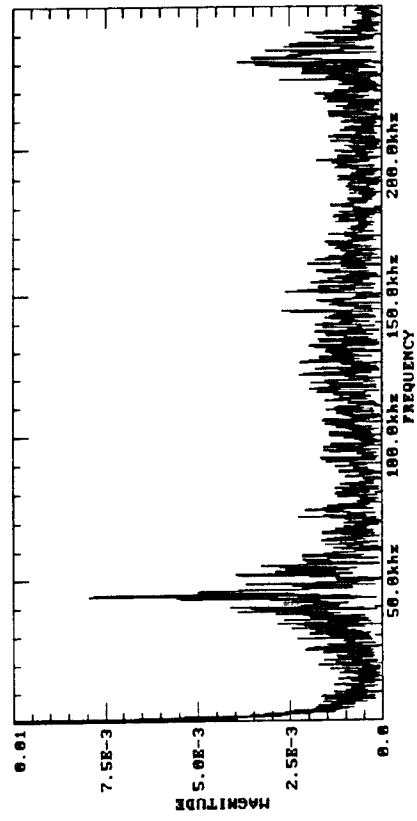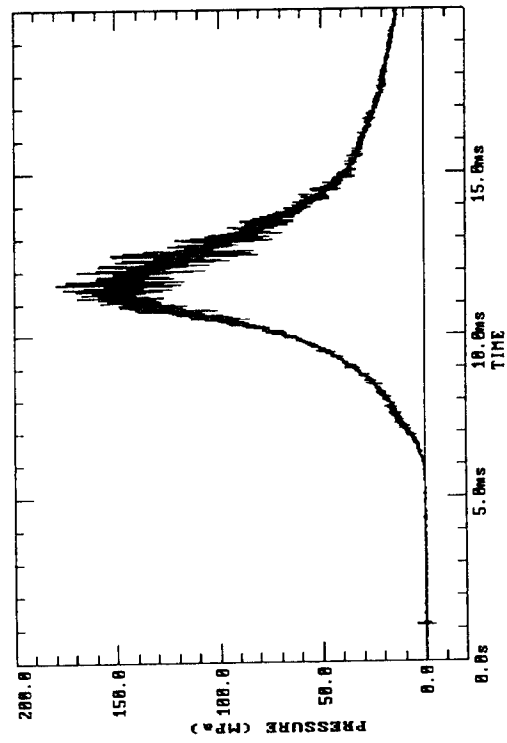
Problems Associated With Signal Conditioning/Acquisition System

Same chamber pressure sampled at 200kHz......

.... with an anti-aliasing filter (LP @ 80 kHz)

.... without an anti-aliasing filter

Conclusions

☐ **Measurement problems evident across the spectrum of advanced propulsion systems**

☐ **Only scratched the surface - many more**

☐ **Measurement techniques need to be refined to allow accurate characterization of "highly-transient, spectrally-rich, combustion environments**

50

APPENDIX B:

PRESENTATION - "COMPARISON OF PRESSURE MEASUREMENTS IN THROUGH PORTS AND STEPPED PORTS"

This Appendix is presented in its original form without editorial changes or comments.
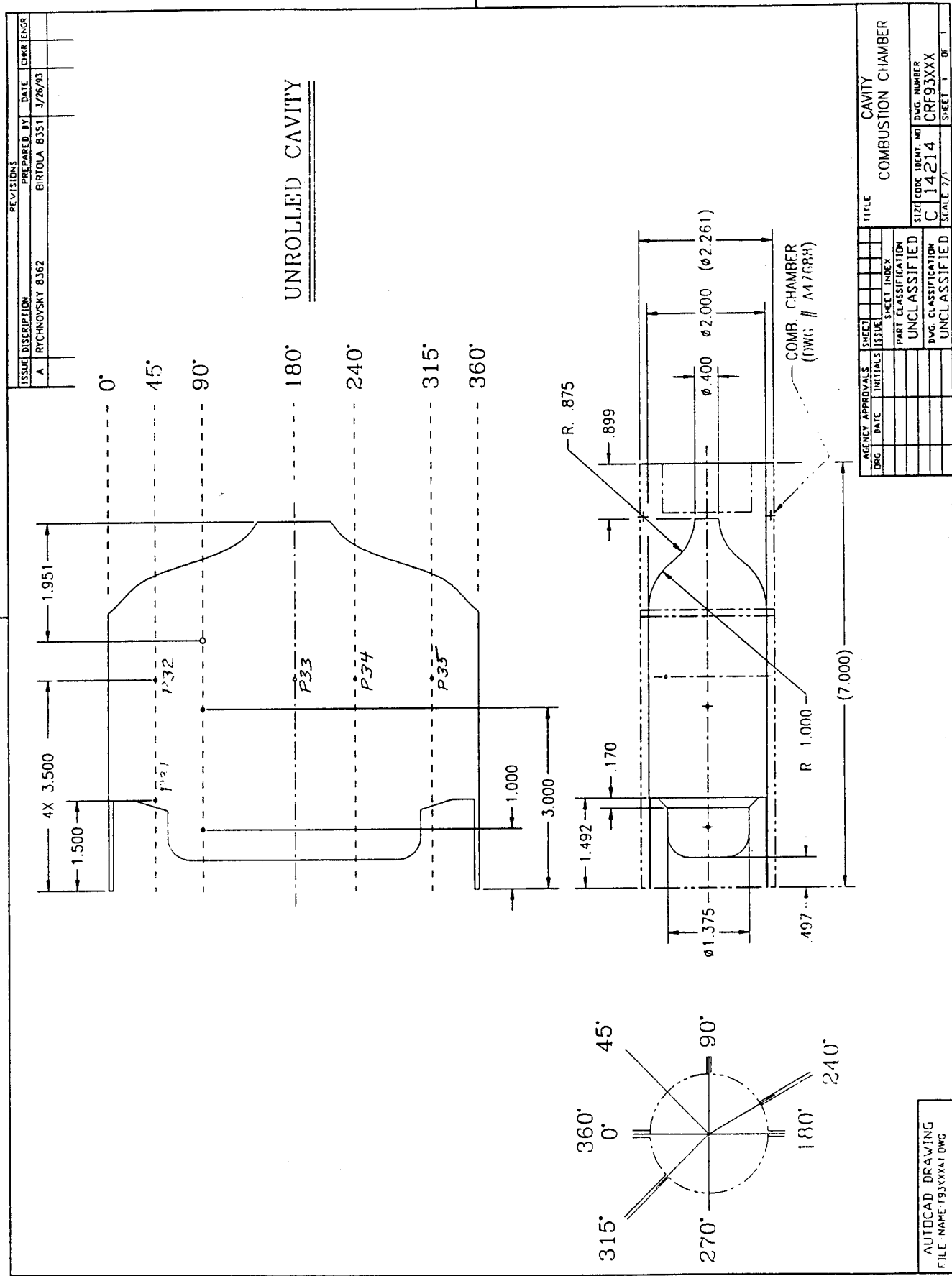
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Comparison of Pressure Measurements in Through Ports and Stepped Ports

R. E. Rychnovsky

Sandia National Laboratories California

Presented at the JANNAF Combustion
Subcommittee Workshop

November 19, 1993
Monterey, California

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UNROLLED CAVITY

COMB. CHAMBER
(DWG. # A47GR3)

Pressure Transducer Hole Inspection

Combustion Chamber
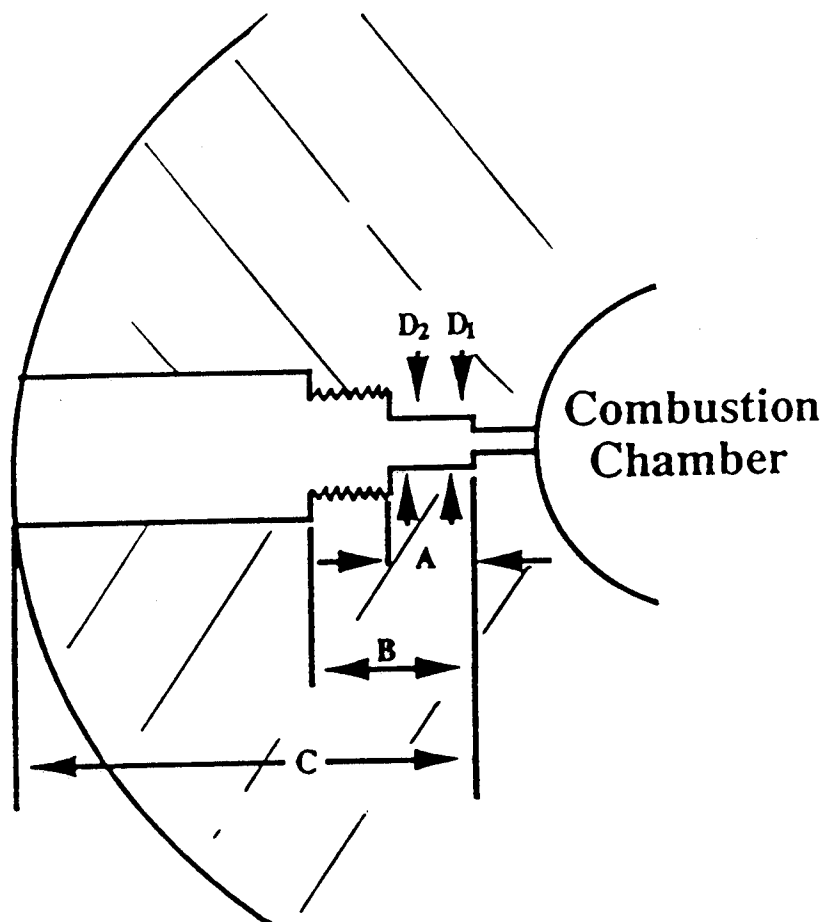
Hole	A	B	C	D_1	D_2
P35	.263	.747	2.888	.252	.252
P34	.265	.747	2.895	.259	.254
P33	.265	.747	2.871	.277	.252
P32	.325	.750	2.889	.276	.251
P31	.277	.752	2.874	.260	.260

Tolerances:
$A \rightarrow .260^{+.010}_{-.000}$

$B \rightarrow .750^{+.005}_{-.005}$

$C \rightarrow 2.906^{+.000}_{-.002}$

D_1 and $D_2 \rightarrow .250^{+.010}_{-.000}$

PCB119

THROUGH HOLE

PCB119
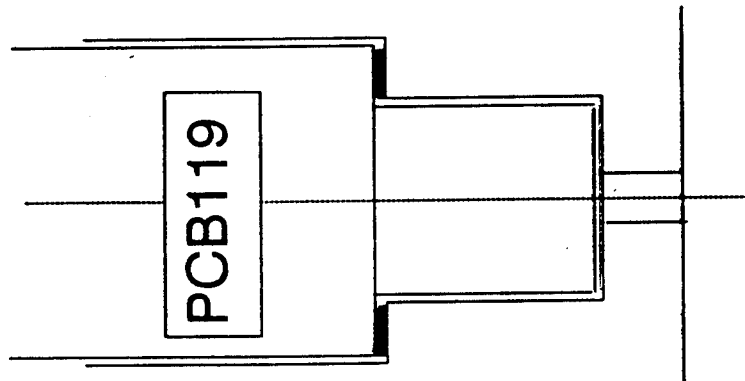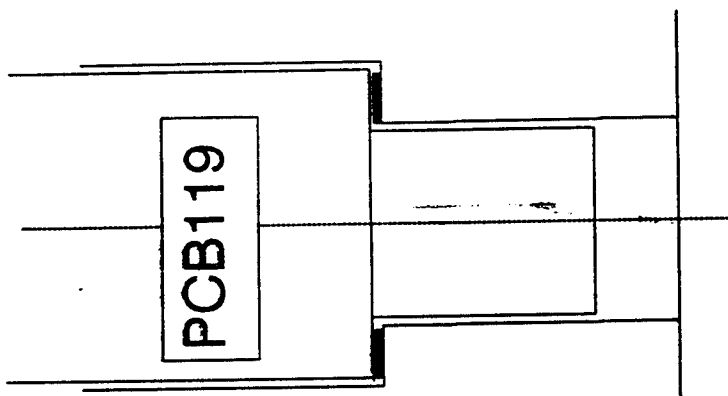
STEPPED HOLE

PRESSURE TRANSDUCER CONFIGURATIONS

UNCLASSIFIED
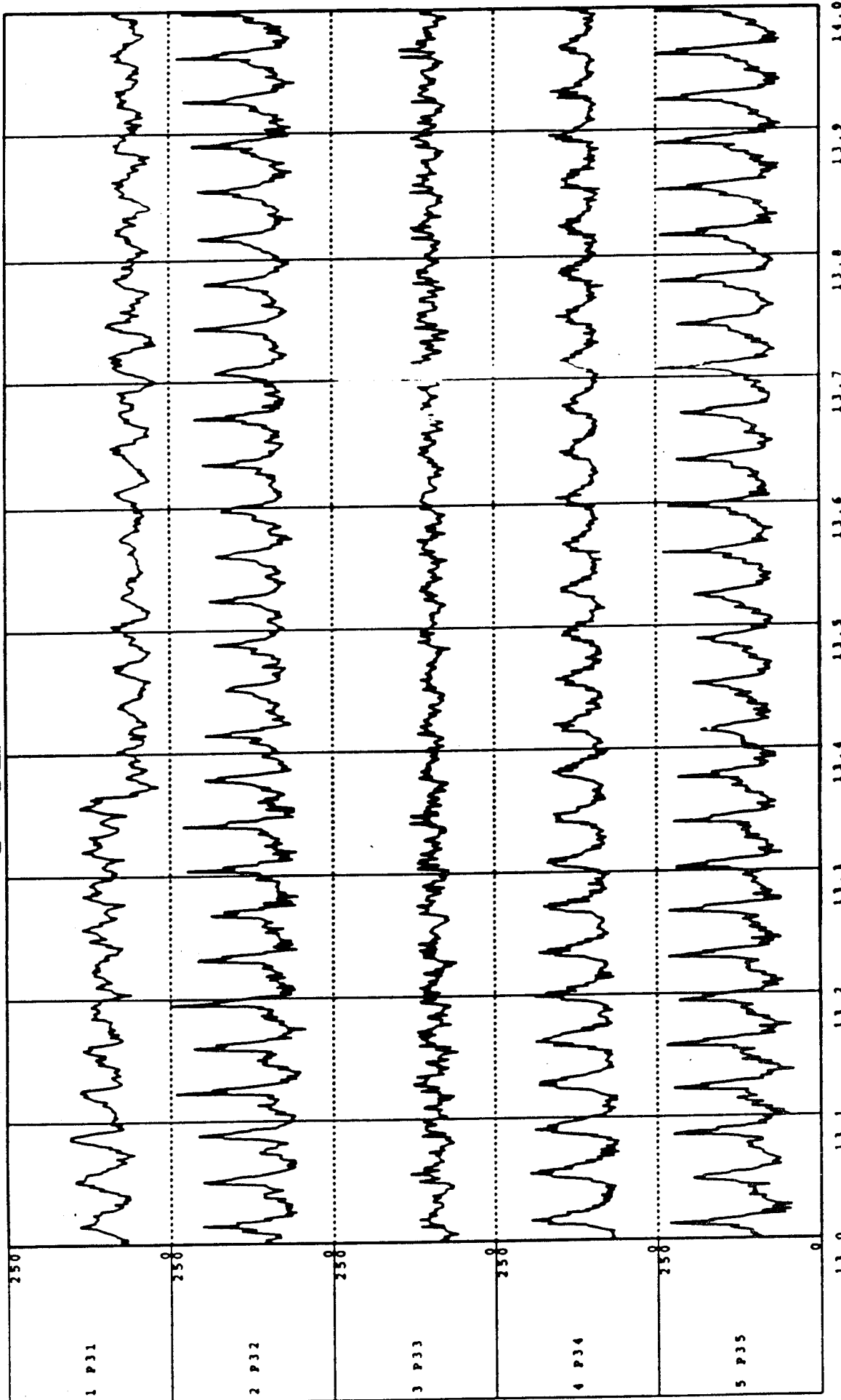
00ct48_000_00 91/02/04 07:47:21   COMBUSTION TEST-48
Catalyst   LPG   100000 samples/sec   CYLIST +
DATA_MILLI_SECONDS = (13 to 14 of 30.207)

MILLI SECONDS

UNCLASSIFIED

MAGNITUDE vs FREQUENCY(HZ)

COMBUSTION TEST-10

80ct48_000_00 91/02/04 07:47:21
Catalyst   LPG   100000 samples/sec   CTLIST +
DATA_MILLI_SECONDS=(13 to 14 of 30.207)   FFT_Delta_Freq = 122.0703 HZ   -DATA_MEAN
(Hanning Windowed)

1 P31
2 P32
3 P33
4 P34
5 P35

0.006
0.010
0.002
0.011
0.010

10^+03   10^+04   10^+05   10^+06

59

UNCLASSIFIED

00oct18_000_00 91/02/04 07:47:21   COMBUSTION TEST-48

[D_C.   5   P35]

DATA_MILLI_SECONDS = (13 to 14 of 30.207)

Catalyst

1000000 samples/sec   CTLYST +

LPG
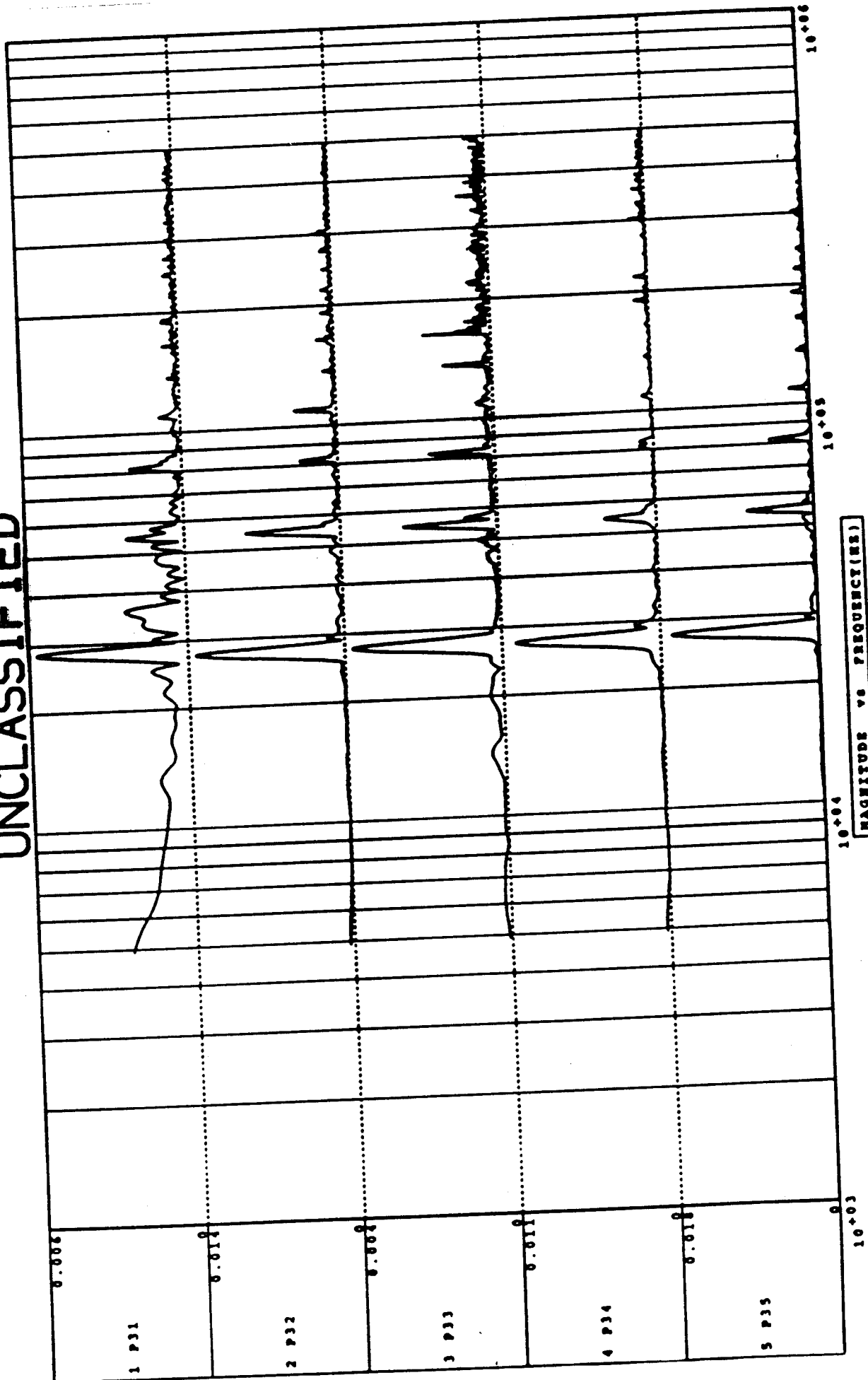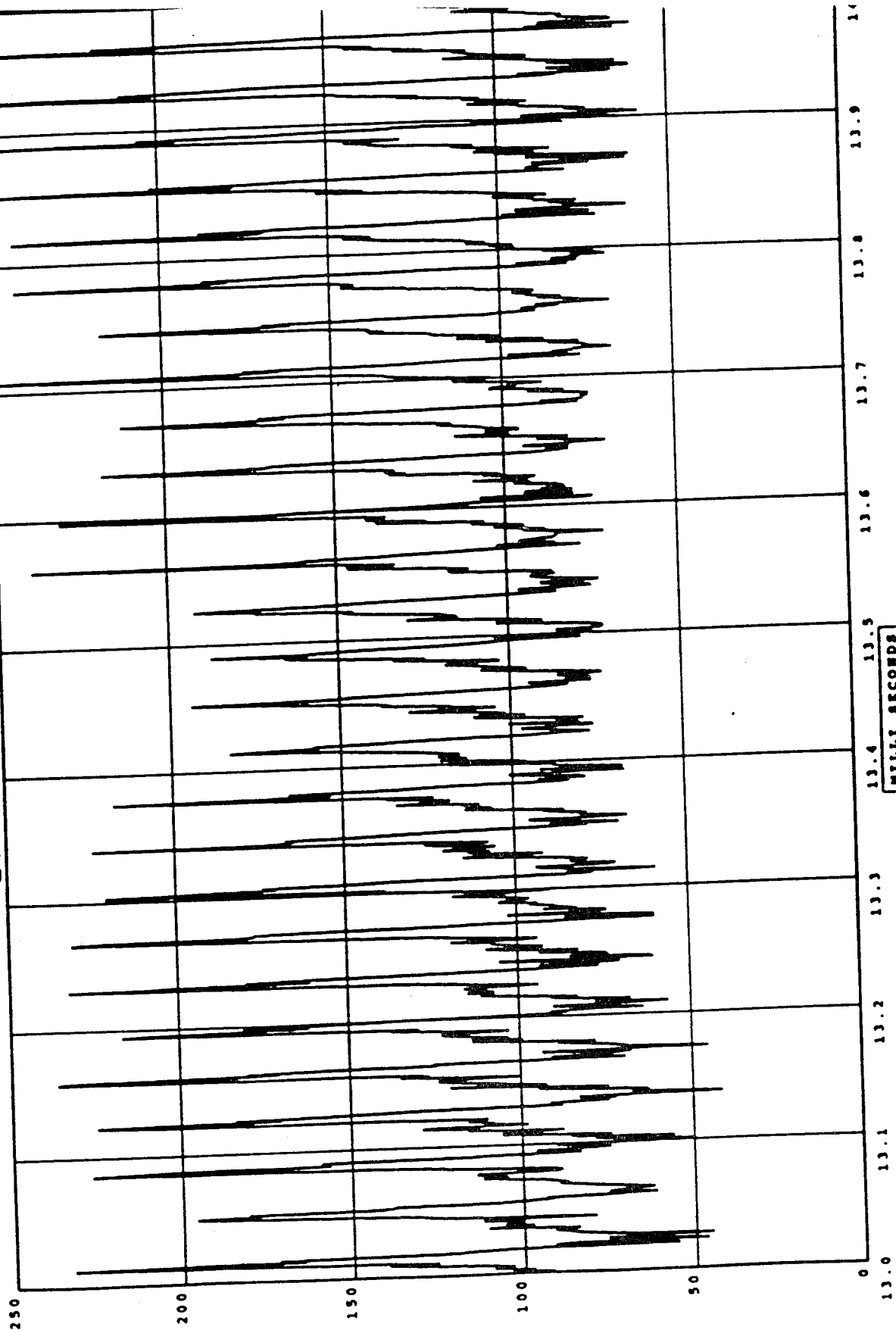
[MILLI SECONDS]

[RAW_DATA-->(1*CHAN + 0.3878)]

[HPA]

60

UNCLASSIFIED

61

00cct48_000_00 91/02/04 07:47:21   COMBUSTION TEST-48

ID C.   2   P32   Catalyst

DATA_MILLI_SECONDS = (13 to 14 of 30.207)

LPG   1000000 samples/sec   CTLYST +

LP COMBUSTION OSCILLATION
TESTS CT-48 TO CT-54
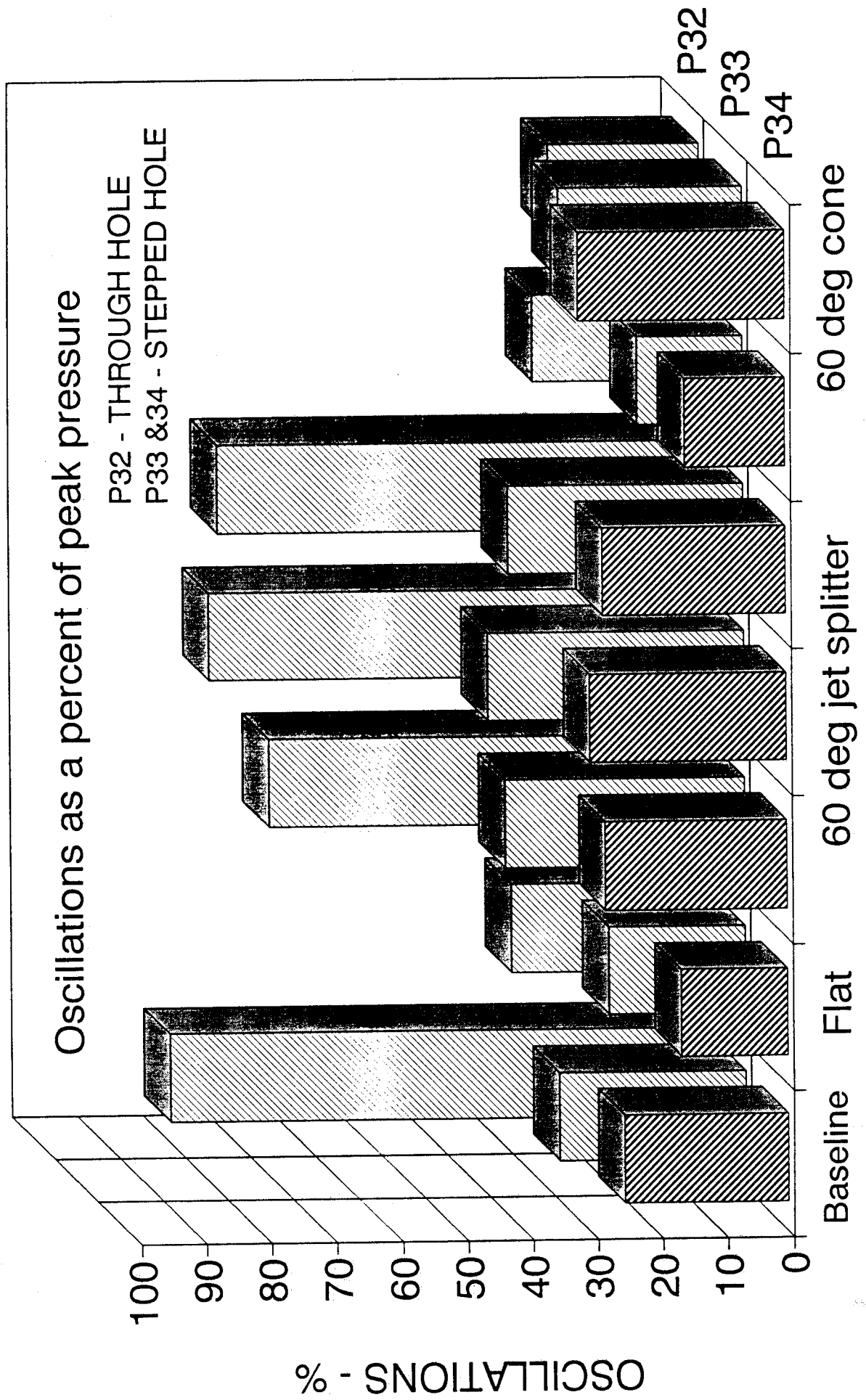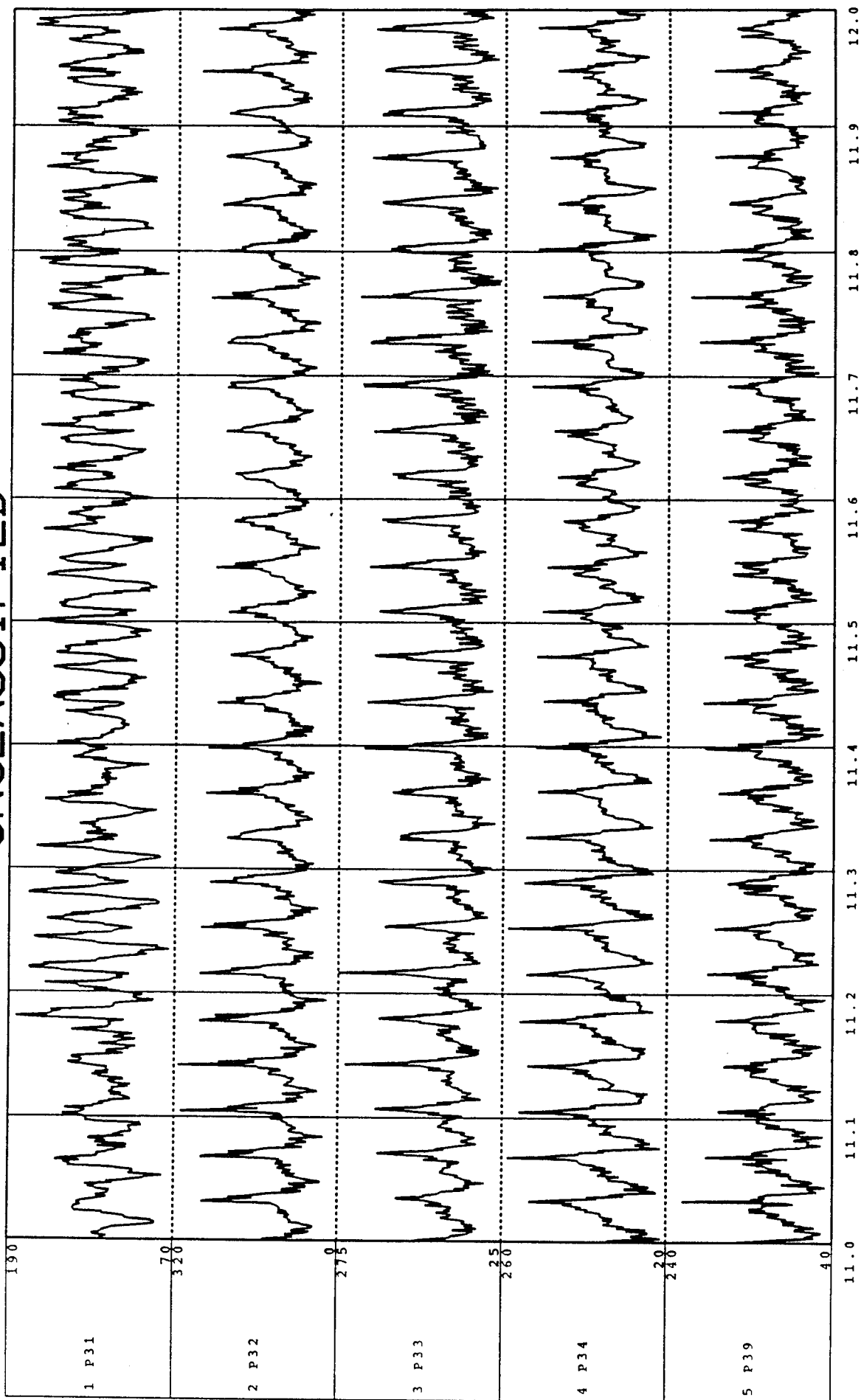
Oscillations as a percent of peak pressure

P32 - THROUGH HOLE
P33 &34 - STEPPED HOLE

P32
P33
P34

100
90
80
70
60
50
40
30
20
10
0

OSCILLATIONS - %

Baseline   Flat   60 deg jet splitter   60 deg cone

62

UNCLASSIFIED

Occt88a_000_00 93/02/02 21:59:50   Combustion Test CCT88A

Catalyst   LPGun   1000000 samples/sec   CTLYST +

DATA_MILLI_SECONDS:<11 to 12 of 40.191>

MILLI SECONDS

63

UNCLASSIFIED
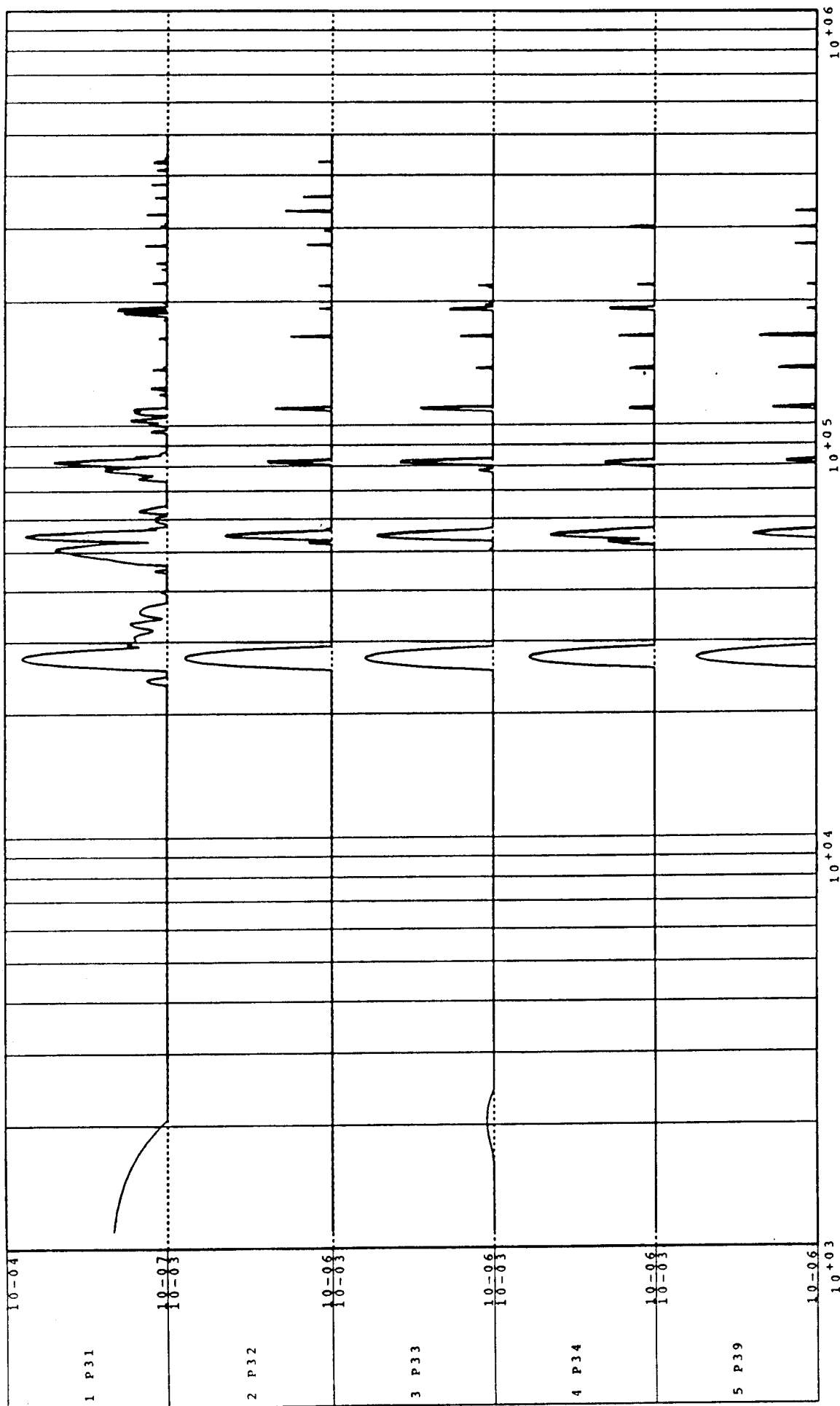
MPA SQ-SEC/HZ vs FREQUENCY(HZ)

Occt88a_000_00 93/02/02 21:59:50   Combustion Test CCT88A
Catalyst   LPGun   1000000 samples/sec   CTLYST +
DATA_MILLI_SECONDS:<11 to 12 of 40.191> FFT_DELTA:122.1HZ -DATA_MEAN
HANNING_WINDOWED

64

The Stepped Pressure Transducer Cavity Severely Filtered the Measured Pressure Oscillations.

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APPENDIX C:

PRESENTATION - "MEASUREMENT OF OSCILLATORY PRESSURE USING SINGLE DIAMETER AND TWO DIAMETER TRANSDUCER CAVITIES"

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Measurement of Oscillatory Pressures Using Single Diameter and Two Diameter Transducer Cavities

G. A. Benedetti
Solid Mechanics Department
Sandia National Laboratories, California

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Measurement of Oscillatory Pressures Using Single Diameter and Two Diameter Transducer Cavities*

G. A. Benedetti
Solid Mechanics Department
Sandia National Laboratories/California

Abstract

Stepped-recessed pressure transducer cavities, which may be grease-filled, are suitable for measuring quasi-static pressure in solid propellant guns and regenerative liquid propellant guns, provided the frequencies contained in the quasi-static pressure pulse are low relative to the fundamental frequency for the empty stepped cavity.

Accurately measured oscillatory pressure-time histories are required to determine the dynamic structural response for projectiles (as well as for guns) and to assess their structural integrity with respect to oscillatory pressure environments in regenerative liquid propellant guns. Unfortunately, grease-filled two diameter cavities or stepped-recessed ports, which have a low fundamental frequency relative to most of the measured frequencies contained in the oscillatory pressures, have been used to measure oscillatory pressures in regenerative liquid propellant guns for many years, and this has resulted in an inaccurate *oscillatory* pressure data base over a large region of the frequency range of interest. Analysis and laboratory experiments both confirm this. Further, the issue of using grease-filled stepped-recessed transducer ports versus grease-filled through-hole transducer ports to measure *oscillatory* pressures has been ongoing for more than two years. There is ample data which shows that grease-filled stepped-recessed cavities are *not* suitable for measuring *oscillatory* pressures over a large region of the frequency range of interest. Therefore, it is strongly recommended that this issue be resolved so that the structural integrity of projectiles in the inventory can be accurately assessed when subjected to the oscillatory pressure environment associated with RLPGs.

REQUIREMENT

- Measurement system requires a flat or one-to-one response (e.g., $p_{out}/p_{in} = 1.0$) over range of frequencies of interest associated with input signal, p_{in}.

- This implies that the cavity natural frequency is significantly higher than the highest frequency of interest in the input signal.

$$e.g., \; f_{nat \; cavity} \geq 5 \; f_{input \; signal}$$

Oscillatory Pressure Measurements

P_{out}
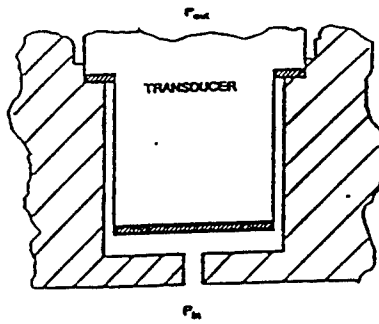
Pressure Transducer and Cavity

Steady State Pressure Response Spectrum
for Transducer Cavity

P_{in}

$$\ddot{x} + 2\zeta\omega_n \dot{x} + \omega_n^2 x = \frac{F_o}{m_p}\sin\omega t$$

$\left|\dfrac{P_{out}}{P_{IN}}\right|$ OR $\left|\dfrac{x\kappa}{F_o}\right|$

$\zeta = \dfrac{c}{c_c}$

Phase angle ϕ

Frequency ratio $\frac{\omega}{\omega_n}$
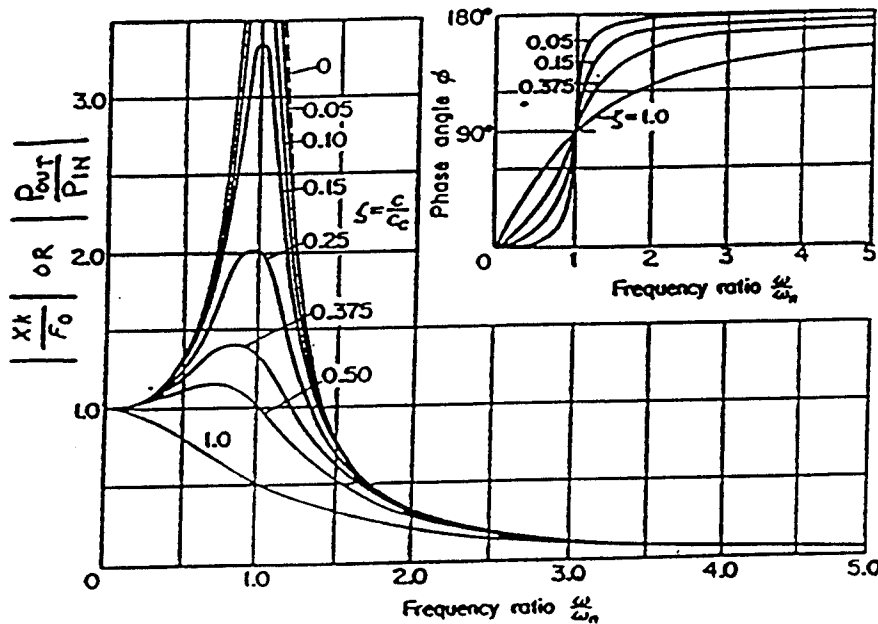
Frequency ratio $\frac{\omega}{\omega_n}$

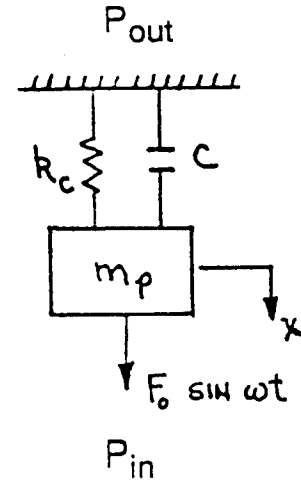Dynamic amplification factor for transducer cavity as a function of frequency ratio and damping factor. ω is the frequency of pressure oscillation (input frequency) at the gun tube wall and ω_n is the first undamped natural circular frequency for the cavity. The phase angle is the angle between the input and output pressures where P_{out} lags P_{in} by the angle ϕ.

73
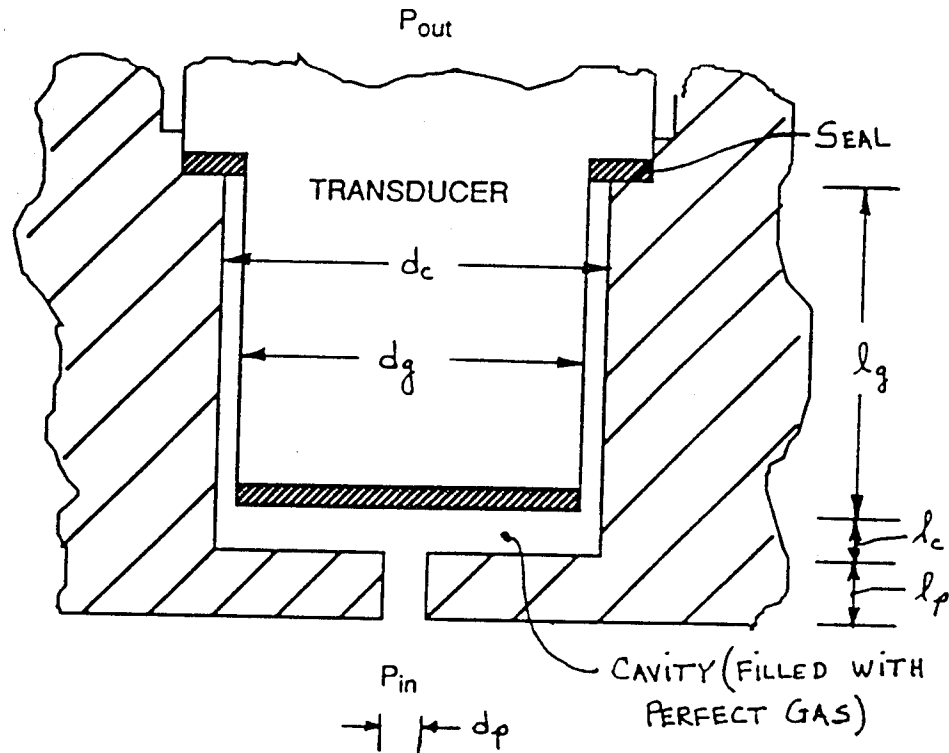
Figure 22. Transducer cavity or stepped-recessed port. Note that the cavity dimensions can vary due to tolerances, machining errors, and installation procedures.

$$f_n = \frac{c_o}{2\pi}\sqrt{\frac{A_p}{V_c \ell_p}}$$

where

$$A_p = \pi d_p^2 / 4$$

$$V_c = \pi d_c^2 \ell_c / 4 + \pi\left(d_c^2 - d_s^2\right)\ell_s / 4$$

c_o = local sound speed

f_n = first undamped natural frequency (in hertz)

* Single Diameter Cavity $\quad t_n = \dfrac{C_o}{4\lambda_p}$

74

Times for a Damped Linear Oscillator to Reach Steady State Vibration

Natural Frequency (kHz)	Natural Period T_n (Millisec)	Time $t_{ss} \simeq T_n/2\zeta_n$ to Reach Steady State for $\zeta_n = 3\%$ (Millisec)
1	1.0	16.67
2	0.5	8.33
4	0.25	4.17
6	0.167	2.78
8	0.125	2.08
16	0.063	1.05
24	0.042	0.70

ACOUSTIC MEASUREMENTS

- CAVITIES NOT FILLED WITH GREASE

- THEORY VERSUS EXPERIMENT

SDOF: 9.1% damping, fn = 5200 Hz

Transmissibility Magnitude

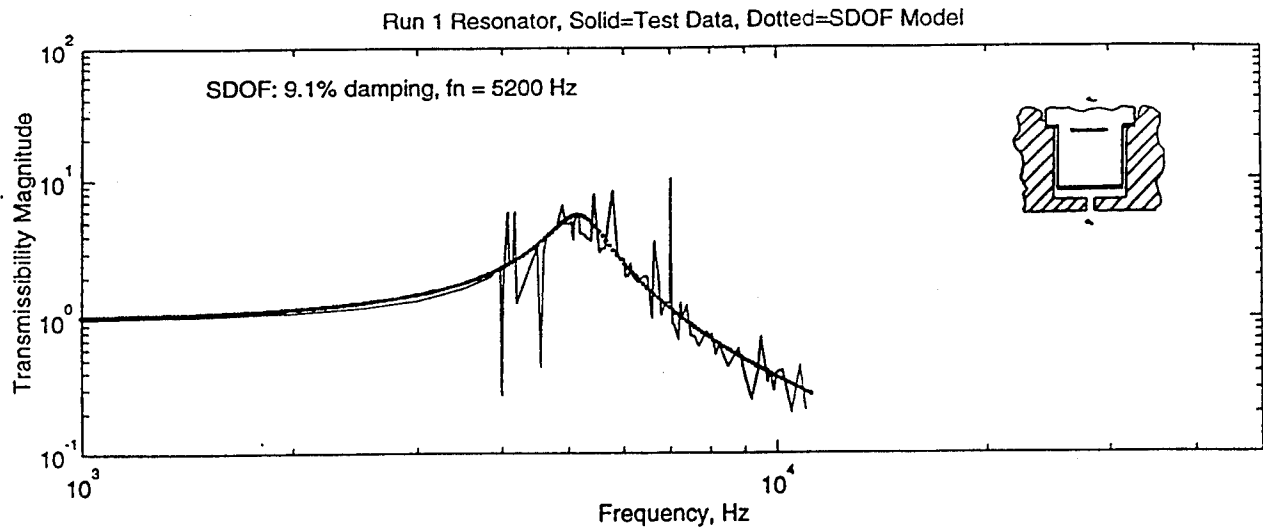Frequency, Hz

Figure 25. Acoustic pressure-frequency response spectrum for a two-diameter or stepped-recessed cavity. Solid line, measured data; dashed line, analytical or predicted data using Eq. (94). The spikes in the measured data result from reflections of the sound wave within the tube, e.g., at 4 kHz the wavelength is 3.4 in. and the circumferential distance between transducers at the same axial location is 1.7 in.; the internal tube diameter is 2 in. and the tube length is 18 in. The internal reflections begin to be significant when the wavelength of the sound wave approaches two times the tube diameter. The local speed of sound is 13,554 in./sec. Cavity dimensions (refer to Figure 22) in inches are: $d_p = 0.058$, $\ell_p = 0.100$, $d_g = 0.234$, $\ell_g = 0.112$, $d_c = 0.242$, $\ell_c = 0.070$. The calculated and measured first natural frequencies for the cavity are 5,830 and 5,200 Hz, respectively. It is suspected that the measured dimensions of the cavity are slightly in error and that the cavity volume is larger than calculated, which would reduce the calculated frequency. The input pressure was measured using a flush-mounted transducer and the output pressure was measured using a transducer mounted in the stepped-recessed cavity. The axial location of the transducers along the tube is identical and equal to 9 in. Note the logarithmic scales on the axes. For further information regarding these series of tests, contact J. D. Rogers, Sandia National Laboratories, Albuquerque, NM.

SDOF: 9.1% damping, fn = 21,600 Hz

Transmissibility Magnitude
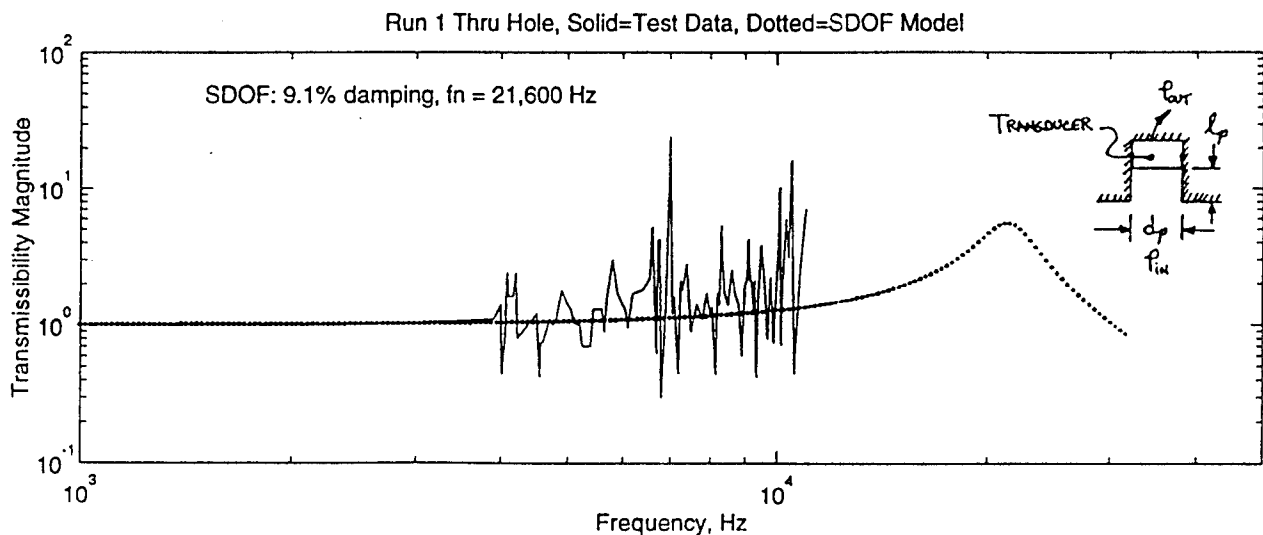
Frequency, Hz

Figure 26. Acoustic pressure-frequency response spectrum for a single-diameter cavity. Solid line, measured data; dashed line, analytical or predicted data using results from Eq. (94) where $\omega_n = 2\pi c_o / 4\ell_p$. Cavity dimensions (in inches) are $d_p = 0.242$, $\ell_p = 0.157$. The calculated first natural frequency for the cavity is 21,600 Hz. The input pressure was measured using a flush-mounted transducer; the output pressure was measured using a transducer mounted in the single-diameter cavity. The axial location of the transducers along the tube is identical. Note the logarithmic scales on the axes. For further information regarding these series of tests, contact J. D. Rogers, Sandia National Laboratories, Albuquerque, NM.
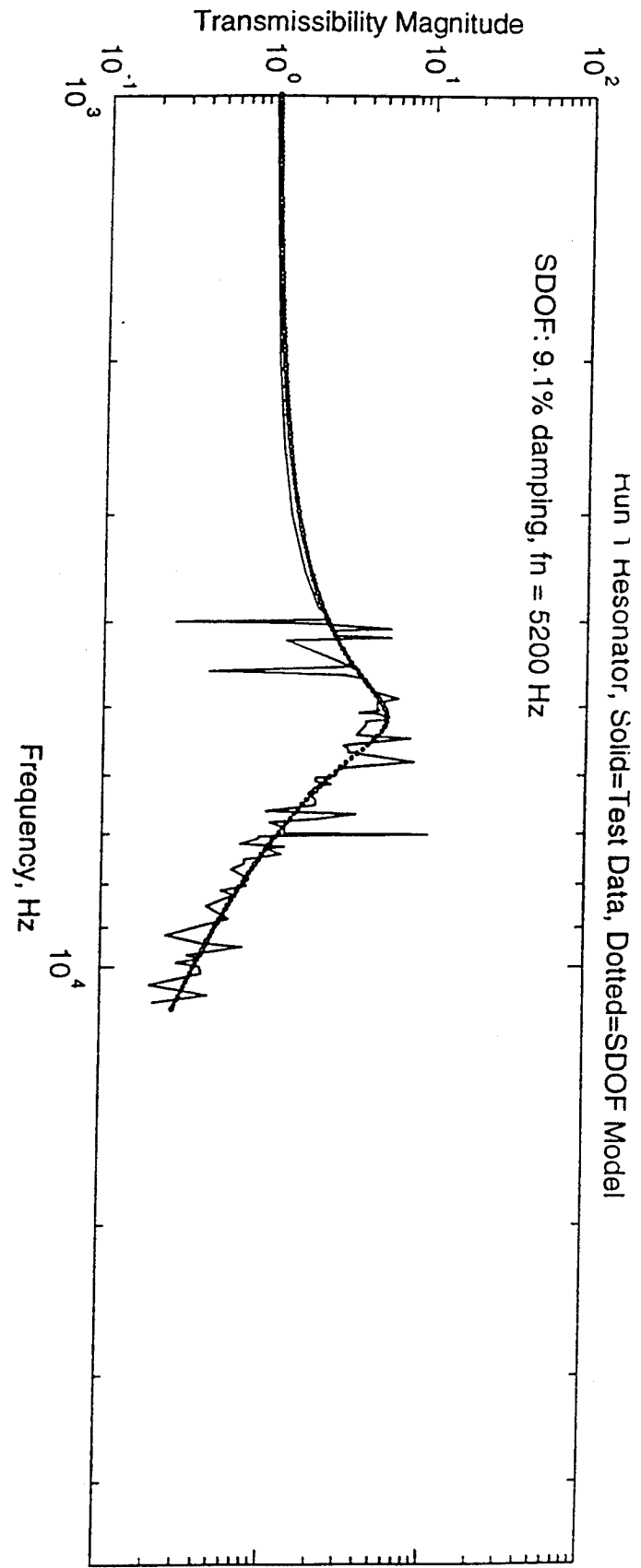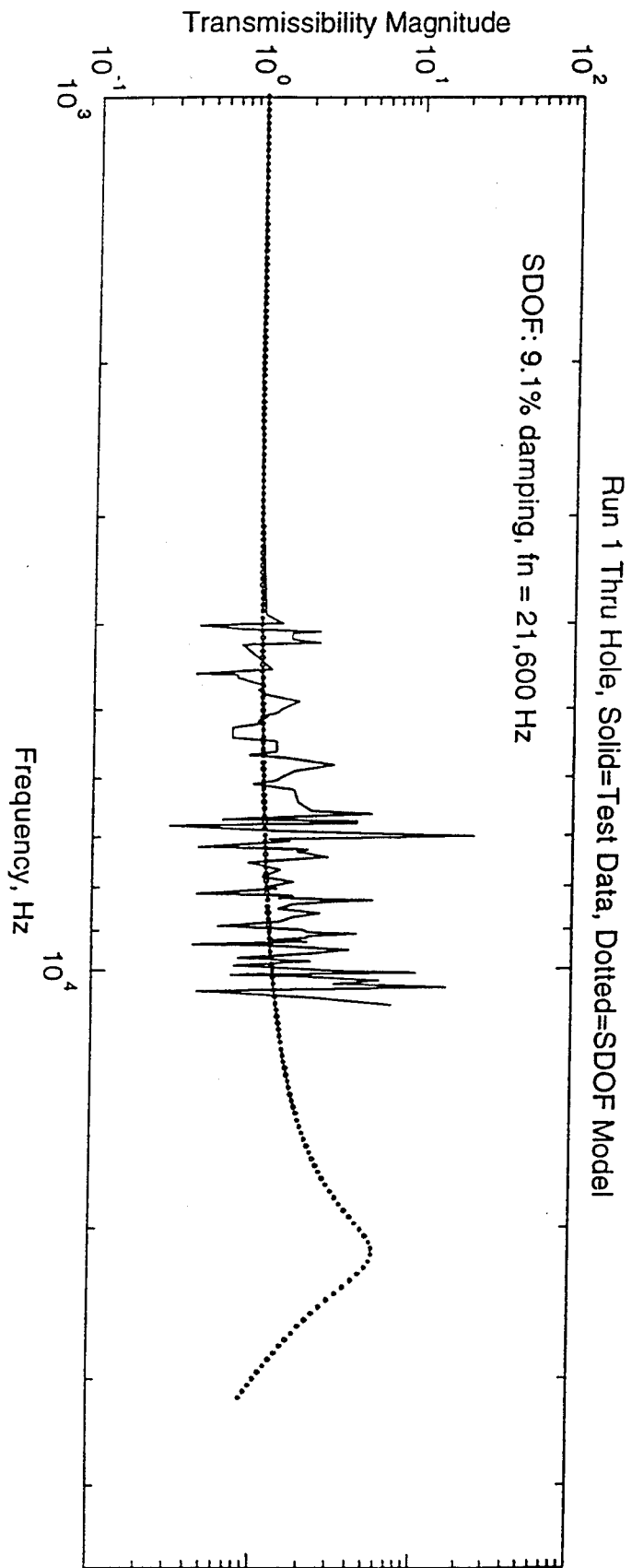
Transmissibility Magnitude

SDOF: 9.1% damping, fn = 5200 Hz

Run 1 Resonator, Solid=Test Data, Dotted=SDOF Model

Frequency, Hz

Transmissibility Magnitude

SDOF: 9.1% damping, fn = 21,600 Hz

Run 1 Thru Hole, Solid=Test Data, Dotted=SDOF Model

Frequency, Hz

78

NON-ACOUSTIC MEASUREMENTS

- CAVITIES FILLED WITH GREASE

- LIQUID COMBUSTOR EXPERIMENT AT SNL/CA

UNCLASSIFIED

Grease-Filled
Through-Hole
f_nat = 96 kHz

Grease-Filled
Stepped Cavity
f_nat = 13.7 kHz

Grease-Filled
Stepped Cavity
f_nat = 20 kHz

Grease-Filled
Through-Hole
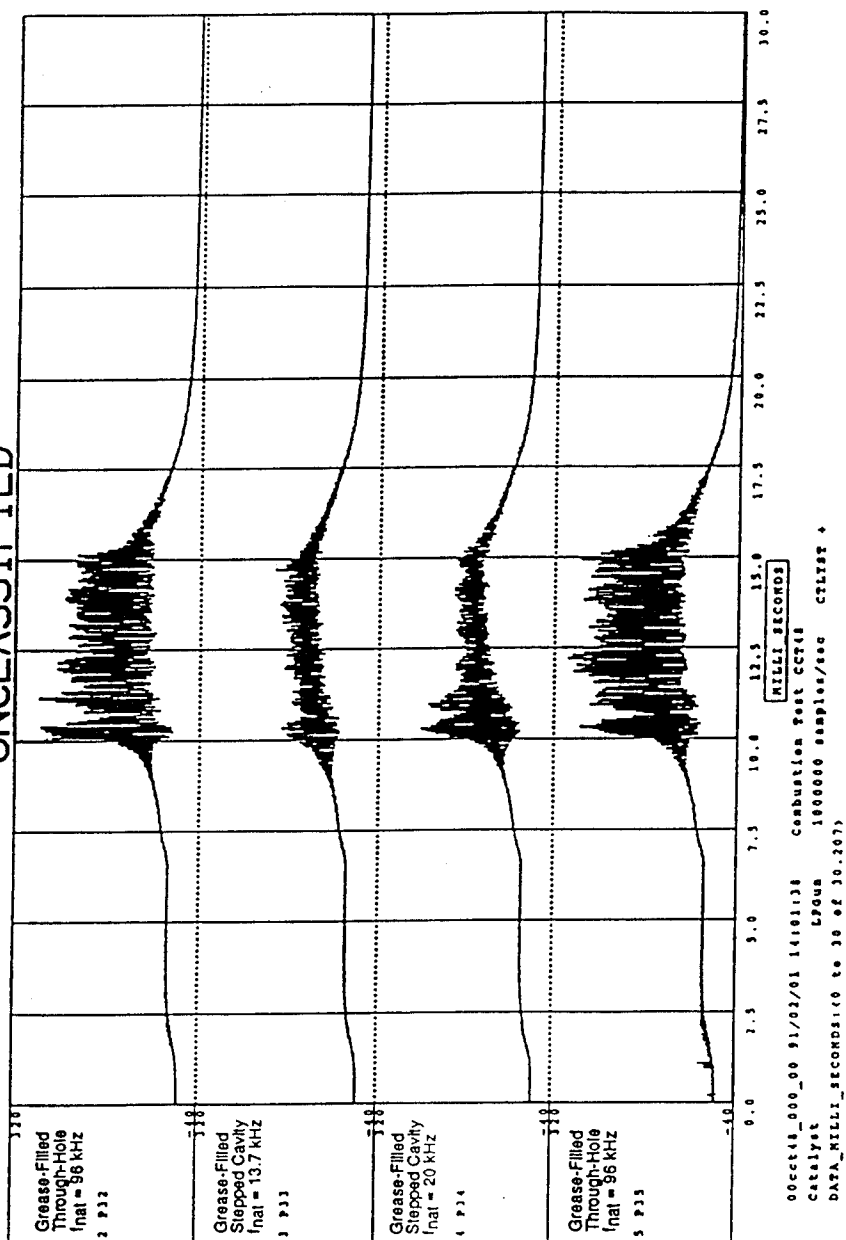f_nat = 96 kHz

MILLI SECONDS

Figure 3.1.   Pressure-time histories for pressure transducers P32 through P35 for combustor test number 48 conducted at SNL/CA, dated Feb. 1991. Each plot has the same vertical scale (-40 MPa to 320 MPa or -5.8 ksi to 46.4 ksi) and a label noting the cavity configuration; i.e., through hole port (0.1 in. deep) or stepped cavity port. Also indicated on each plot is the calculated acoustic first natural frequency for the cavity. These calculations used the actual cavity dimensions and a local sound speed of 3200 ft/sec. The pressure transducers, P32 through P35, are located at the same axial station and spaced circumferentially in 90° increments. Before the test, each cavity was filled with Dow Corning 3451 silicone grease. After the test, the grease was gone from each cavity. It is not apparent from the data when the grease leaves the cavity.

Note the following:
1.   The through hole ports, P32 and P35, give very similar results especially with respect to the oscillatory pressure measurements.

2.   The stepped cavity ports, P33 and P34, grossly attenuate the magnitude of the oscillatory pressure. P33 attenuates the oscillatory pressure magnitude more than P34.
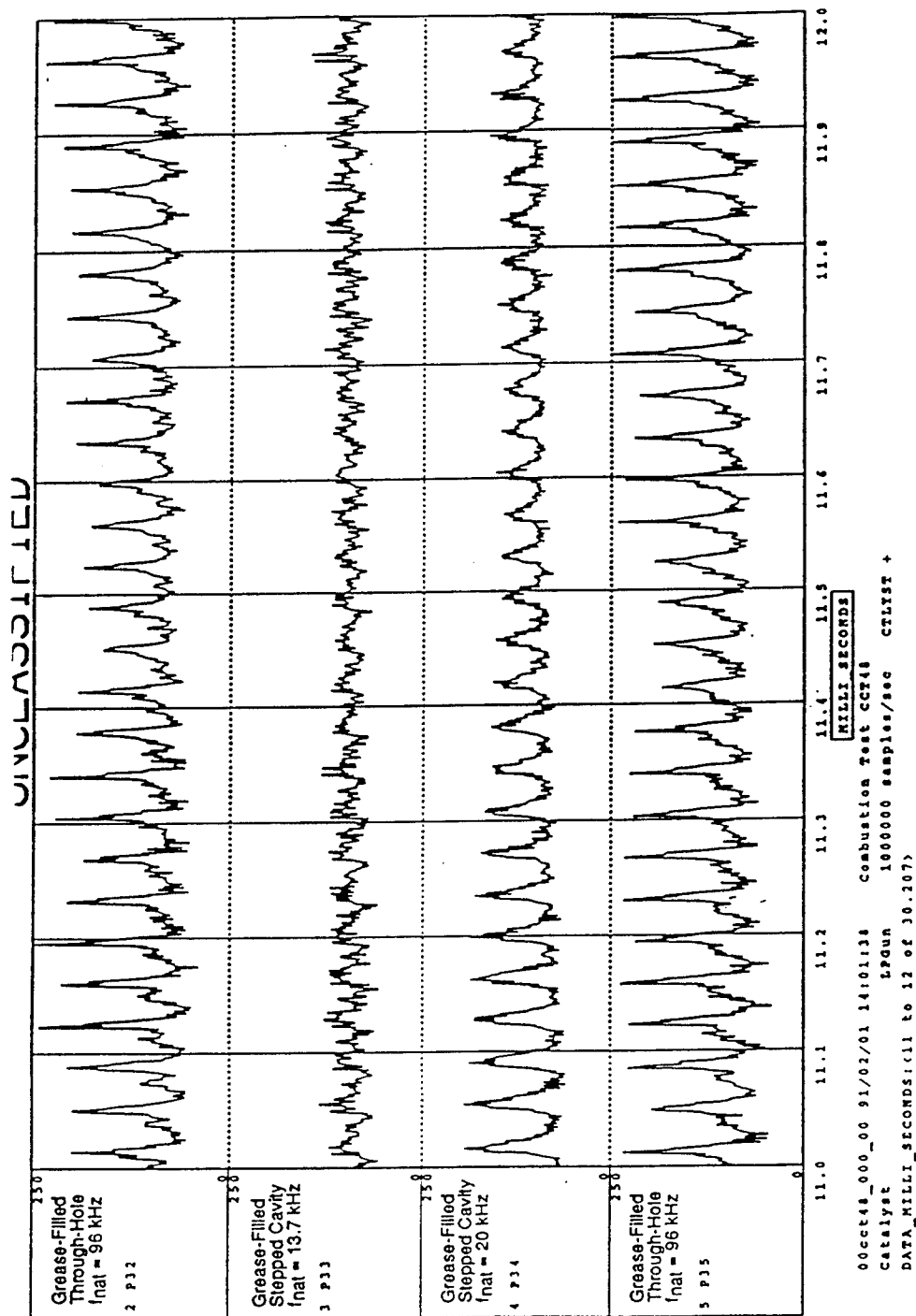
80

Figure 3.2.   Expanded time scale (11 to 12 milliseconds) for pressure-time histories shown in Figure 3.1.

Note the following:

1. The through hole ports, P32 and P35, give very similar results especially with respect to the oscillatory pressure measurements.

2. The stepped cavity ports, P33 and P34, grossly attenuate the magnitudes of the oscillatory pressure. P33 attenuates the oscillatory pressure more than P34. This is expected since the frequency ratio (f_{input}/f_{nat}) for P33 (~2.04) is greater than for P34 (~1.4).

3. The stepped cavity ports, P33 and P34, give significantly different results for the measured oscillatory pressures because their first natural frequencies are significantly different due to dimensional tolerances and machining errors.

81

Figure 3.3. Magnitudes of Fourier transform of pressure-time histories shown in Figure 3.2.

Note the following:
1. The through hole ports, P32 and P35, give nearly identical results for the tranform magnitudes.

2. The stepped cavity ports, P33 and P34, grossly attenuate the magnitudes of the oscillatory pressure. As expected, P33 attenuates the oscillatory pressure more than P34.
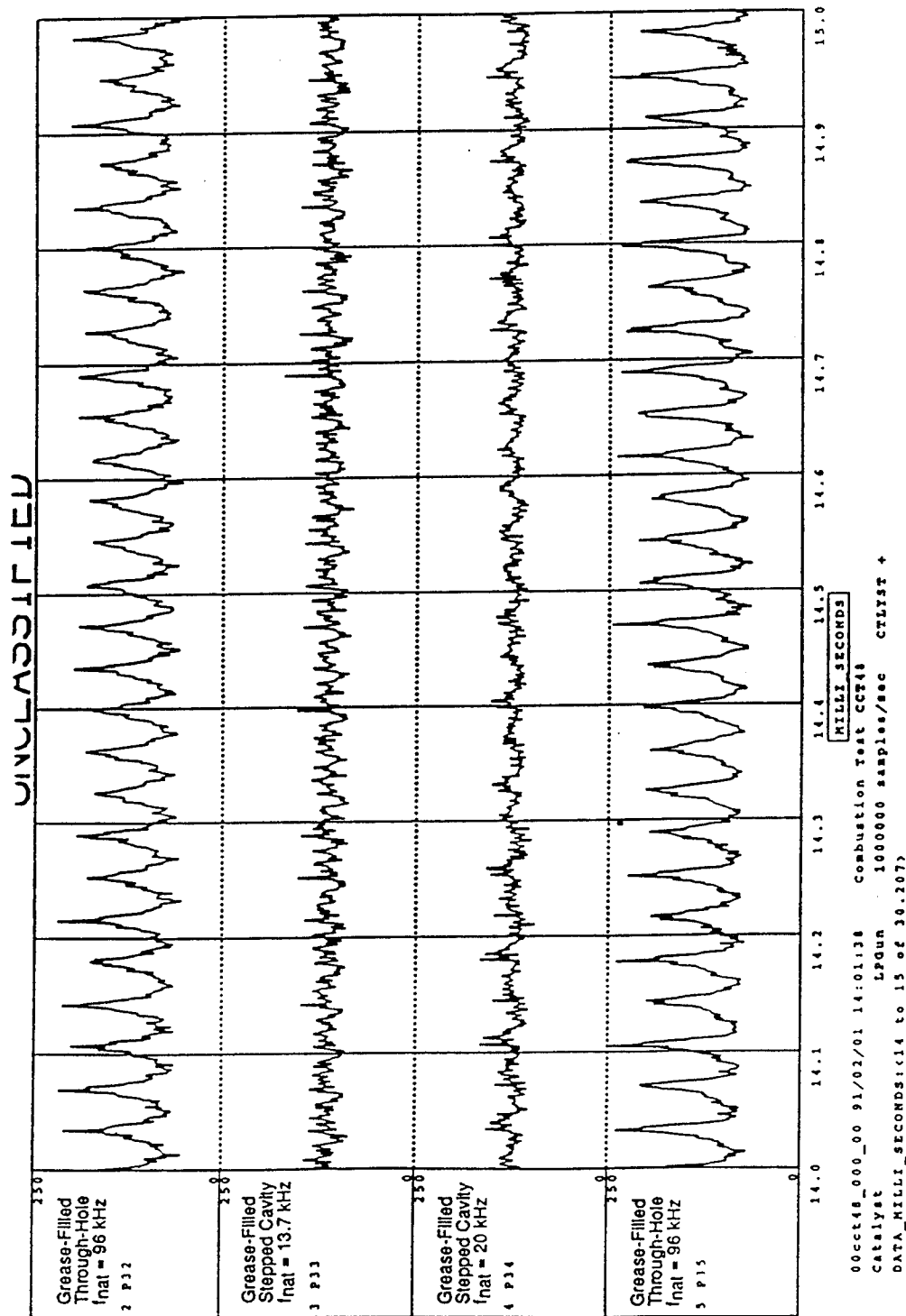
Figure 3.4   Expanded time scale (14 to 15 milliseconds) for pressure-time histories shown in Figure 3.1.

Note the following:
1. The through hole ports, P32 and P35, give very similar results for the oscillatory pressure.

2. The stepped cavity ports, P33 and P34, grossly attenuate the magnitude of the oscillatory pressure.

3. The stepped cavity ports, P33 and P34, give significantly different results for the measured oscillatory pressures because their first natural frequencies are significantly different due to dimensional tolerances and machining errors.
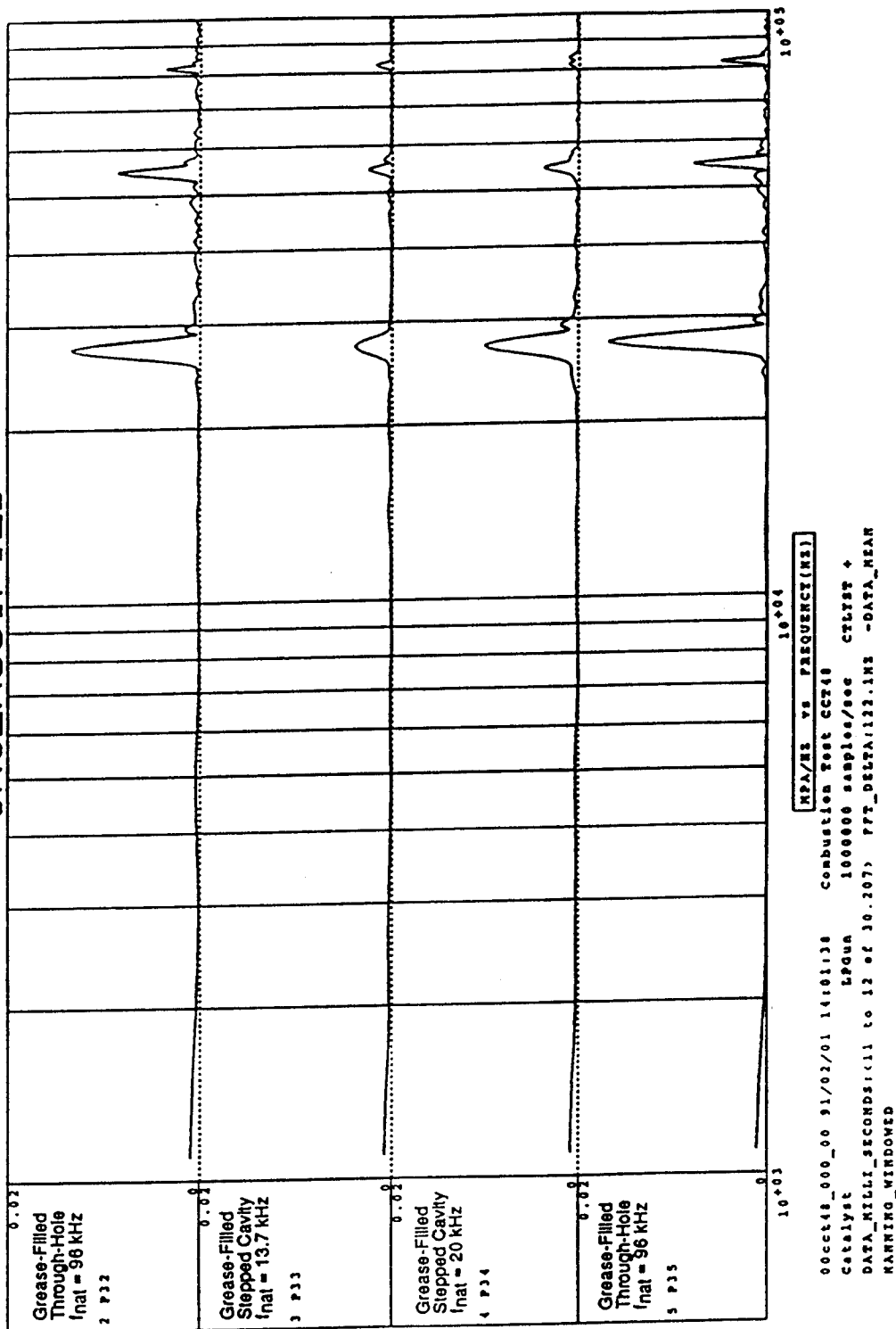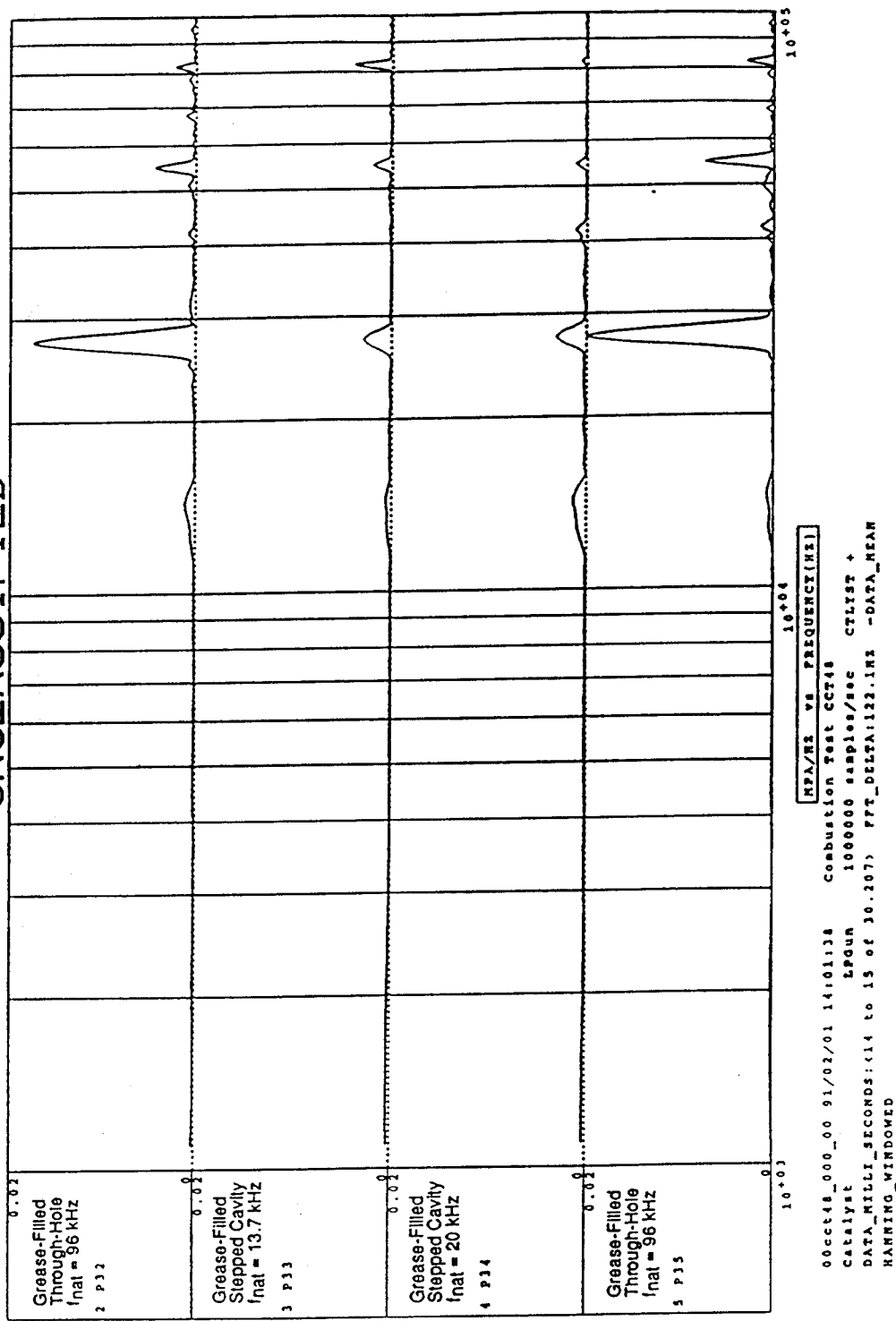
Figure 3.5   Magnitudes of Fourier transform of pressure-time histories shown in Figure 3.4.

Note the following:
1. The through hole ports, P32 and P35, give nearly identical results for the transform magnitudes.

2. The stepped cavity ports, P33 and P34, grossly attenuate the magnitudes of the oscillatory pressure.

Table 1

Measurement Error for Max.Oscillatory Pressure

n	F/F_{max}	f (kHz)	$(1-F/F_{max}) \times 100 =$ Error, %
2	0.463	80	53.7
3	0.743	53.3	25.7
4	0.851	40	14.9
5	0.903	32	9.7
6	0.933	26.7	6.7
8	0.962	20.0	3.8
10	0.975	16.0	2.5
12	0.983	13.3	1.7

$$f = \frac{c_0}{\lambda}$$

$$\lambda = nd$$

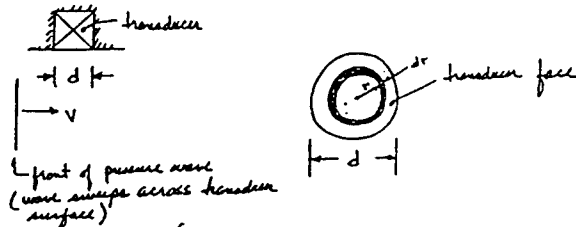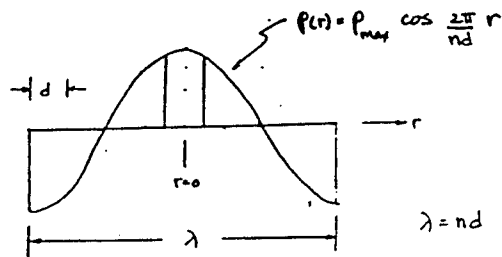$$c_0 \cong 40 \times 10^3 \text{ inches/sec}$$

$$d \cong 0.25 \text{ inches}$$

$$\% \text{ error} = \left\{ 1 - \frac{2n}{\pi} \left[\frac{n}{\pi} (-1 + \cos \frac{\pi}{n}) + \sin \frac{\pi}{n} \right] \right\} \times 100$$

$$f = \frac{c_0}{nd}$$

To simplify integration; assume $p = p(r)$.

$$p(r) = p_{max} \cos \frac{2\pi}{nd} r$$

$$\lambda = nd$$

$$F = \int_A p(r) \, dA = \int_r p(r) \, 2\pi r \, dr$$

CONCLUSIONS

- Accurately measured oscillatory pressure-time histories are required to determine the dynamic structural response for projectiles (as well as for guns) and to assess their structural integrity with respect to oscillatory pressure environments in regenerative liquid propellant guns.

- Filling through-hole and stepped cavity pressure gage (transducer) mounting ports with grease **does not** mitigate gross differences between measured oscillatory pressures.

- Stepped-recessed pressure transducer cavities, which may be grease-filled, are suitable for measuring quasi-static pressure in solid propellant guns and regenerative liquid propellant guns, provided the frequencies contained in the quasi-static pressure pulse are low relative to the fundamental frequency for the empty stepped cavity.

CONCLUSIONS

- Most of the oscillatory pressure measurements in liquid propellant guns have been made using a stepped cavity where the fundamental frequency of the cavity is *low* (rather than *high*) compared to the highest measured input frequency of interest. Consequently, the accuracy of the measured oscillatory pressure data base is severely limited relative to the frequency range of interest (e.g., up to 50 kHz).

- It is strongly recommended that this issue be resolved so that the structural integrity of projectiles in the inventory can be accurately assessed when subjected to the oscillatory pressure environment associated with RLPGs.

- Accurate high frequency oscillatory pressure measurements depend not only on the transducer's cavity configuration, frequency response of the measurement system, etc., but also on the *diameter of the transducer's sensing element.*
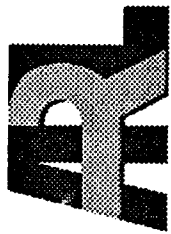
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APPENDIX D:

PRESENTATION - "FURTHER EVIDENCE OF THE EFFECTS OF TWO DIAMETER TRANSDUCER CAVITIES ON PRESSURE MEASUREMENTS"

*This Appendix is presented in its original form without
editorial changes or comments.*

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ARL

Weapons Technology Directorate

Propulsion & Flight Division

Measurement Techniques in Highly-Transient Spectrally-Rich Combustion Environments Workshop

Further Evidence of the Effects of Two-Diameter Transducer Cavities on Pressure Measurements

Jim DeSpirito, Nathan Boyer, Todd Rosenberger, Joe Colburn

U.S. Army Research Laboratory

Aberdeen Proving Ground, Maryland 21005-5066

30th JANNAF Combustion Subcommittee Meeting

Hyatt Regency Hotel & Naval Postgraduate School

Monterey, California

15-19 November 1993
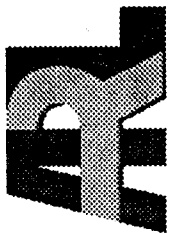
The Environment

- Typical RLPG pressure.
  - Oscillations begin at about 80 to 100 MPa.
  - Frequencies range from about 7 kHz to greater than 50 kHz in 30-mm.

Weapons Technology Directorate

Concept VI-C RLPG

A-plane

B-plane

3.18 cm

6.22 cm

PROJECTILE

COMBUSTION
CHAMBER

LP
RESERVOIR

CONTROL PISTON

DAMPER

REAR BLOCK

INJECTION PISTON

NOT DRAWN TO SCALE

93

Pressure Gage Port Design

1-Diameter Port

Ø 0.50
C'BORE

0.375−24
UNF−2B
THD

Ø $\frac{0.2505}{0.2500}$

0.335
±.002

2-Diameter Port

Ø 0.50
C'BORE

0.375−24
UNF−2B
THD

Ø 0.094
(or Ø 0.060)

Ø $\frac{0.2505}{0.2500}$

0.245
±.002

0.090

94

Background

- **REFERENCE:** "Measurement of Pressure Oscillations in Regenerative Liquid Propellant Guns," letter from Dr. G.A. Benedetti, Sandia National Laboratories, to Mr. Kok Chung, ARDEC, March 1992.

  - Used acoustic analysis to show that 2-diameter, recessed gage ports may limit the frequency response spectrum (acts like Helmholtz resonator).

  - A 1-diameter through port, recessed less than 0.030" is necessary for acceptable frequency response in the RLPG.

  - Acoustic analysis predicted attenuation in SNL Injector/Combustor test fixture.

  - The effect of packing with grease or RTV is unknown.

- Two tests (P55 & P57) with no packing in 1-diameter port (A90) and 2-diameter port (A120).

- Related references:

  - Benedetti, G.A., "Dynamic Response of a Transducer Mounted at One End of an Acoustical Cavity," Sandia Report SAND92-8003, UC-705, April 1993.

  - Rogers, J.D., "Pressure Gage Port Investigation," summary report prepared for US Army ARDEC by Sandia National Laboratories, February 1993.
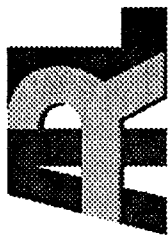
Gage Port Geometry

$$f_n = \frac{c}{2\pi}\sqrt{\frac{A}{\ell\, V_o}} \qquad (2-dia\ port)$$

$c = speed\ of\ sound\ (38,400\ in/s)$

$$A = \frac{\pi}{4} d_p^2$$

$$\ell = l_p$$

$$V_o = \frac{\pi}{4}\left\{ l_c d_c^2 + 0.25\left[d_c^2 - (0.246)^2 \right]\right\}$$

$$f_n = \frac{c}{4 l_p} \qquad (1-dia\ port)$$
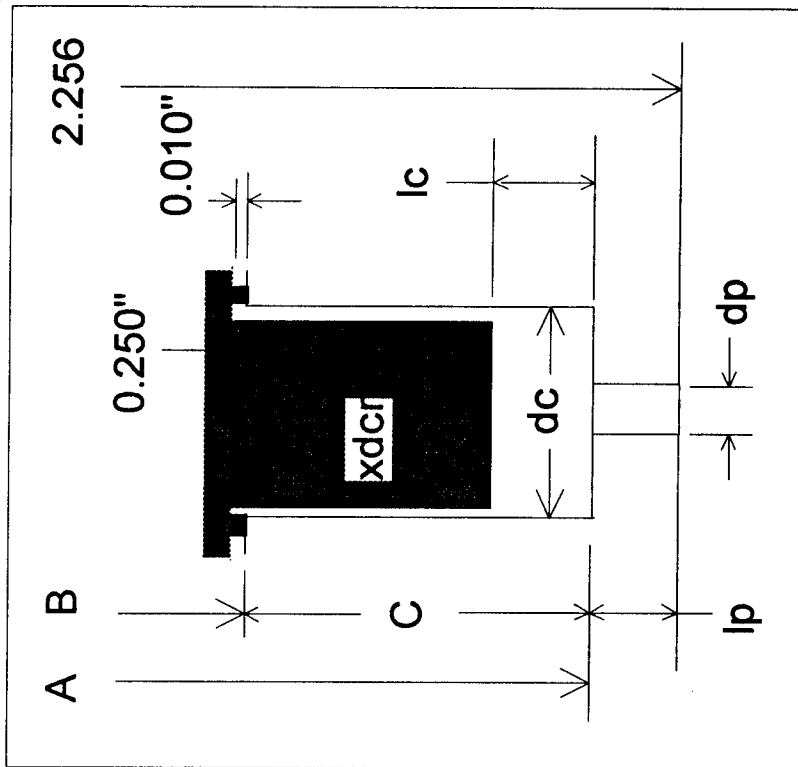
Gage Port	dp in	Ap in^2	lp in	lc in	dc in	Vc in^3	Fn kHz
A30	0.065	3.32E-03	0.072	0.050	0.2505	2.89E-03	24.4
A120	0.059	2.73E-03	0.072	0.006	0.2505	7.17E-04	44.5
A90							101

2.256

0.010"

0.250"

lc

xdcr

dc

dp

A B

C

lp

96
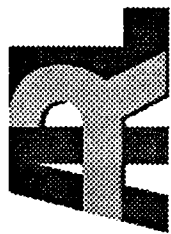
Test P55

Chamber Pressure : Mean Removed

Test P57

Chamber Pressure : Mean Removed

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Weapons Technology Directorate

98
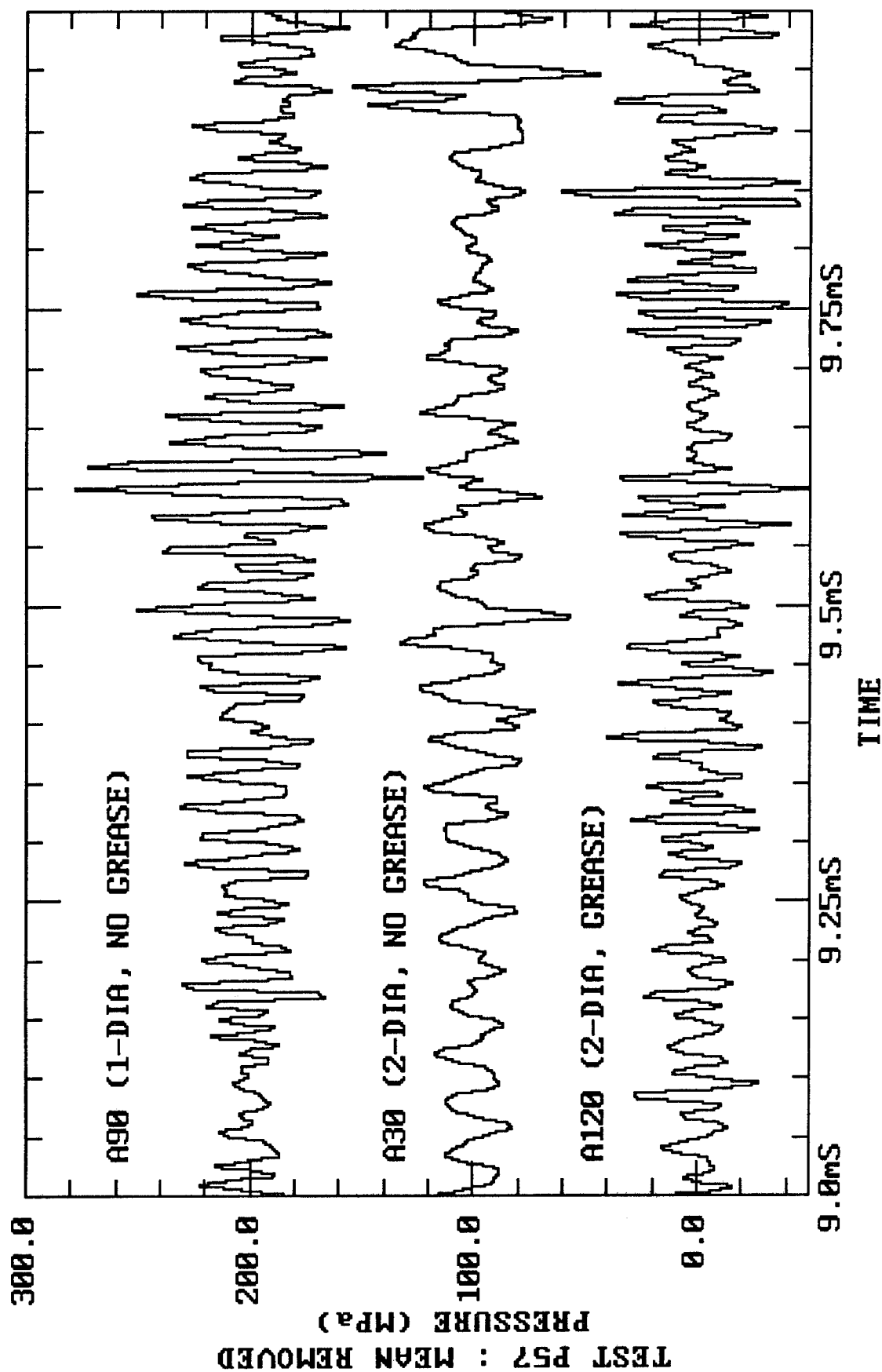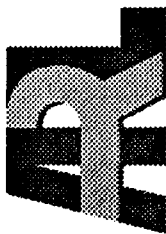
Test P55
Gage Port Frequency Analysis

- Analysis performed at five frequencies shown below.
- One-diameter port (A90, solid line) used as input pressure.
- Two-diameter port without packing material (A30, dotted line, top) follows response predicted by acoustic analysis.
- Two-diameter port packed with grease (A120, dotted line, bottom) does not follow response predicted by acoustic analysis.
  - » Good match of input pressure to 20 kHz.
  - » Signal attenuated above 20 kHz.
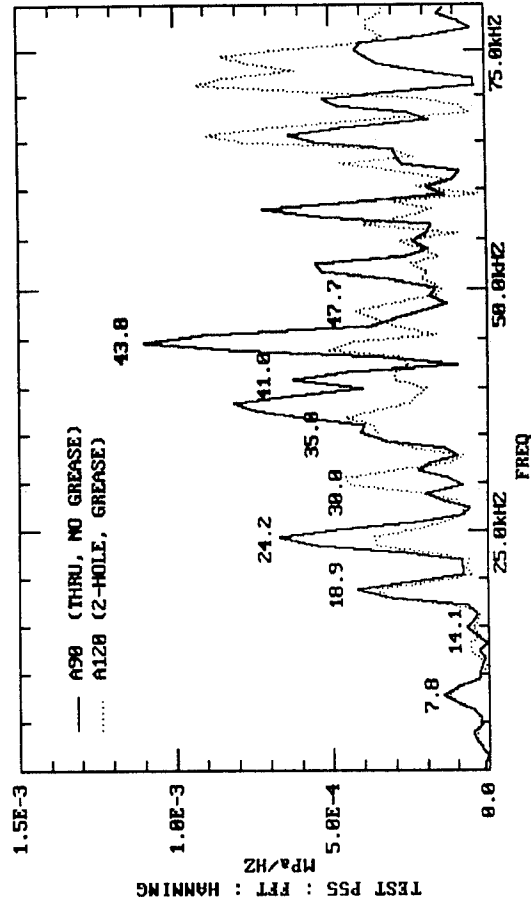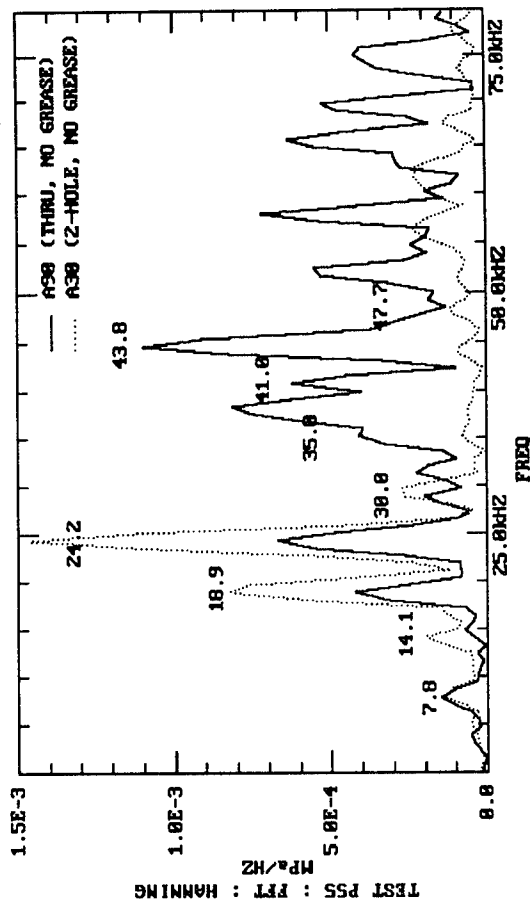
Freq (kHz)	Gage Port	F/Fn	(Po/Pi)m	(Po/Pi)A90	(Po/Pi)m*	(Po/Pi)c
7.8	A30	0.32	0.94	1.01	0.95	1.10
	A120	0.18	0.90		0.91	1.05
14.1	A30	0.58	4.49	1.02	4.58	1.50
	A120	0.32	0.70		0.71	1.10
18.9	A30	0.77	1.94	1.04	2.02	2.50
	A120	0.42	0.85		0.88	1.20
24.2	A30	0.99	2.18	1.08	2.37	>3.5
	A120	0.54	0.54		0.59	1.30
43.8	A30	1.80	0.11	1.27	0.15	0.35
	A120	0.98	0.61		0.84	>3.5

Test P57
Gage Port Frequency Analysis

- Analysis performed at five frequencies shown below.
- One-diameter port (A90, solid line) used as input pressure.
- Two-diameter port without packing material (A30, dotted line, top) follows response predicted by acoustic analysis.
- Two-diameter port packed with grease (A120, dotted line, bottom) does not follow response predicted by acoustic analysis.
  » Good match to input pressure to 20 kHz.
  » Signal attenuated above 20 kHz.
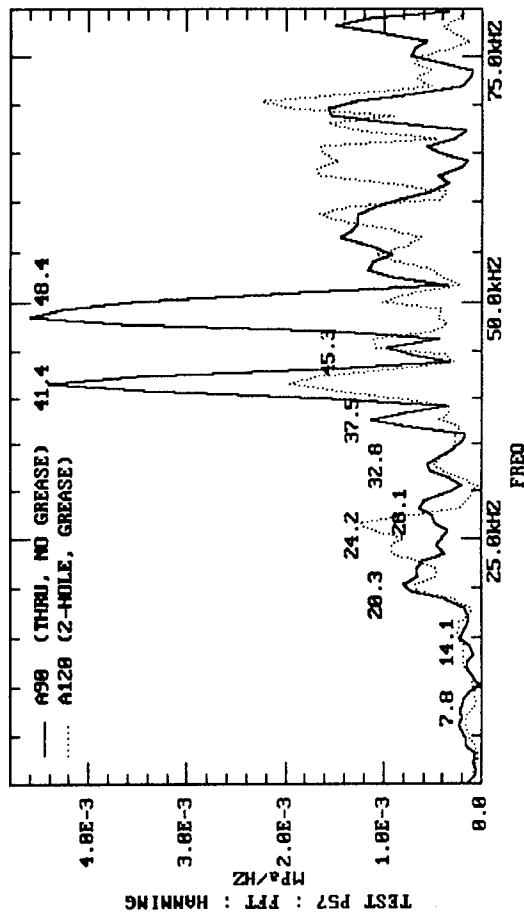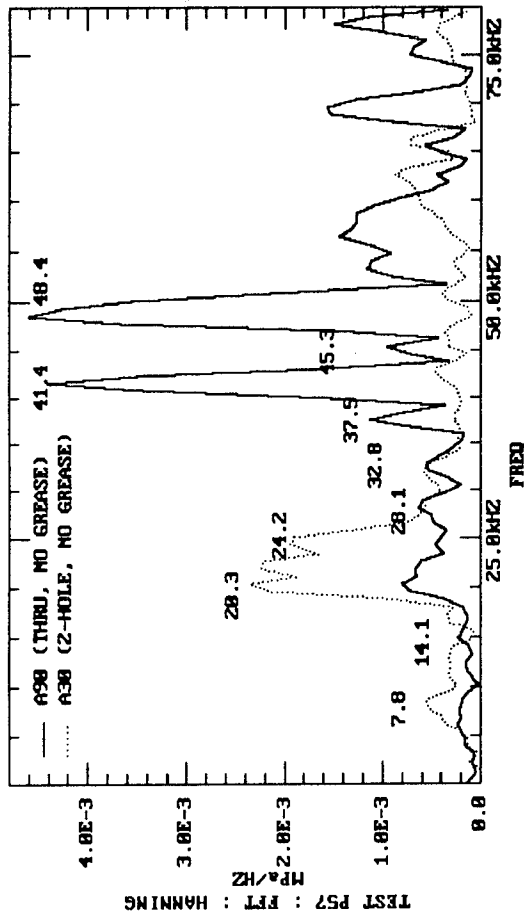
Freq (kHz)	Gage Port	F/Fn	(Po/Pi)m	(Po/Pi)A90	(Po/Pi)m*	(Po/Pi)c
7.8	A30	0.32	2.50	1.01	2.53	1.10
	A120	0.18	0.37		0.37	1.05
14.1	A30	0.58	2.23	1.02	2.28	1.50
	A120	0.32	1.54		1.57	1.10
20.1	A30	0.77	2.39	1.05	2.52	2.50
	A120	0.42	0.85		0.89	1.20
24.2	A30	0.99	4.17	1.08	4.53	>3.5
	A120	0.54	1.98		2.15	1.30
45.3	A30	1.80	0.36	1.31	0.52	0.35
	A120	0.98	1.14		1.65	>3.5

Summary

- **One-diameter port used as input pressure.**

  – Some amplification of signal is possible, depending on length of recess.

  – Trade-off between frequency response and mean signal validity.

- **Two-diameter port without packing material follows response predicted by acoustic analysis.**

  – Signal amplified near natural frequency of gage port.

  – Signal attenuated at frequencies well above the natural frequency.

- **Two-diameter port packed with grease does not follow response predicted by acoustic analysis.**

  – Good match to input pressure to 20 kHz.

  – Signal attenuated above 20 kHz.
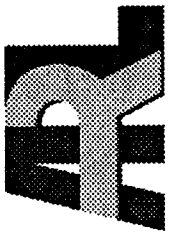
Conclusions

- Mean pressure not measurably affected by design of gage port in these tests.

- One-diameter port without grease is best for measuring frequency response.

- Natural Frequency of 2-diameter port without packing is too low for studying RLP gun oscillations.

- Two-diameter port with grease packing is better, but high frequencies are still attenuated.

  – What are the physical properties of the grease at gun pressures?

  – *When does the grease go away?*
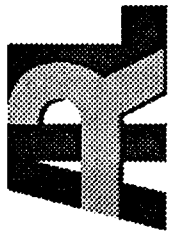
Suggested Procedure

For tests in which oscillations must be studied:

1. Use both 2-diameter ports with grease and 1-diameter ports without grease.

2. Use low-pass filtered pressure-time history from 2-diameter port to define the "quasi-static," or mean pressure.

3. Use pressure-time from the 1-diameter port, with mean pressure (with likely thermal drift effects) removed, to define the oscillatory pressure history.

4. Oscillatory pressure-time history may then be super-imposed on mean pressure-time history.

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APPENDIX E:

PRESENTATION - "HIGH FREQUENCY PRESSURE OSCILLATIONS IN THE IN BORE RAMJET ACCELERATOR"

This Appendix is presented in its original form without editorial changes or comments.

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HIGH FREQUENCY PRESSURE OSCILLATIONS IN THE INBORE RAMJET ACCELERATOR

D. Kruczynski

J. Colburn

Presented at the "Measurement Techniques in Highly-Transient, Spectrally-Rich Combustion Environments" Workshop

19 November 1993
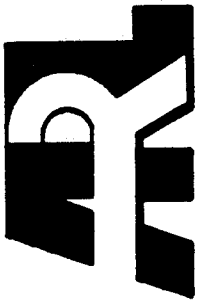
OUTLINE

- Compare FFT's performed on pressure and strain data from a gun tube similar to section 1 of HIRAM

- Compare gun data FFT's with HIRAM data FFT

- Compare FFT's of pressure traces recorded during an inert HIRAM firing using "stepped" and "through" pressure transducer mounting ports

- Conclusions

- Future work/directions

Operation of a Ram Accelerator

Gun Tube

Combustion

Pre-mixed gaseous propellant

Oblique Shocks
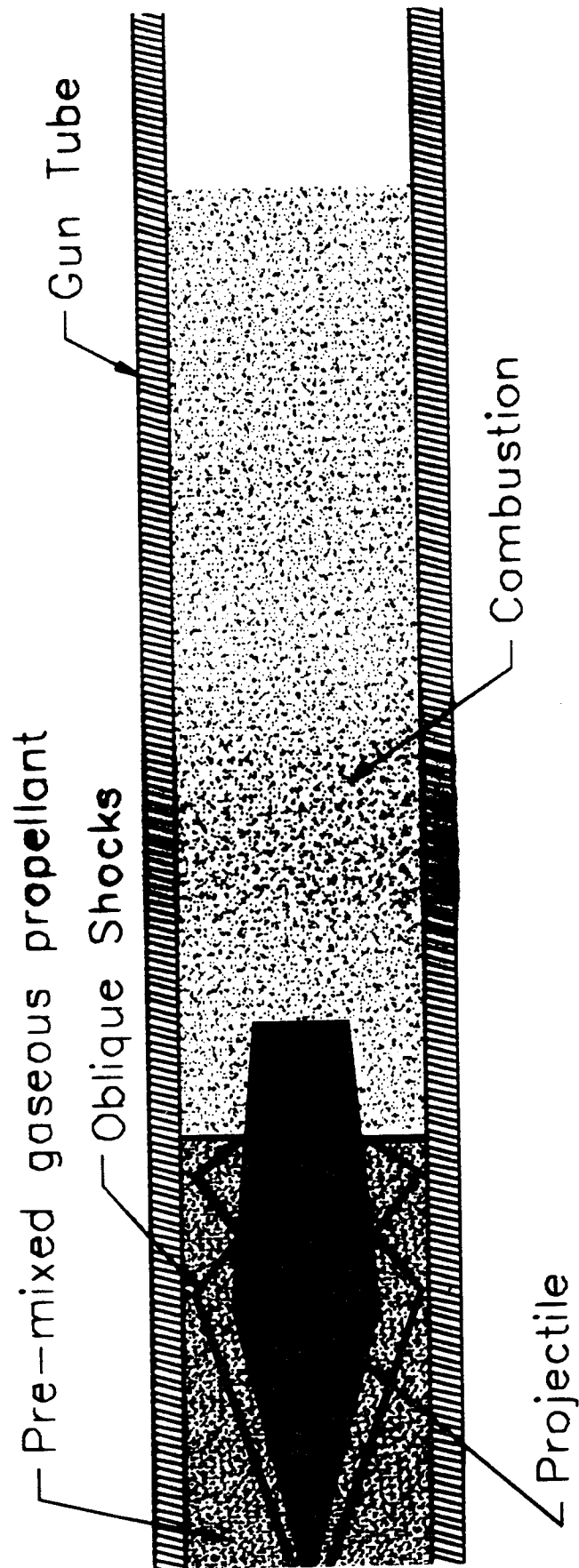
Projectile

Computed and Experimental Pressure Distributions

Tube Wall
4-Fin Projectile

Computed

Experimental

2.7CH$_4$+2O$_2$+5.8N$_2$
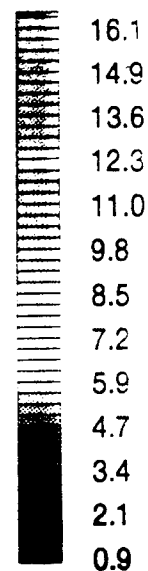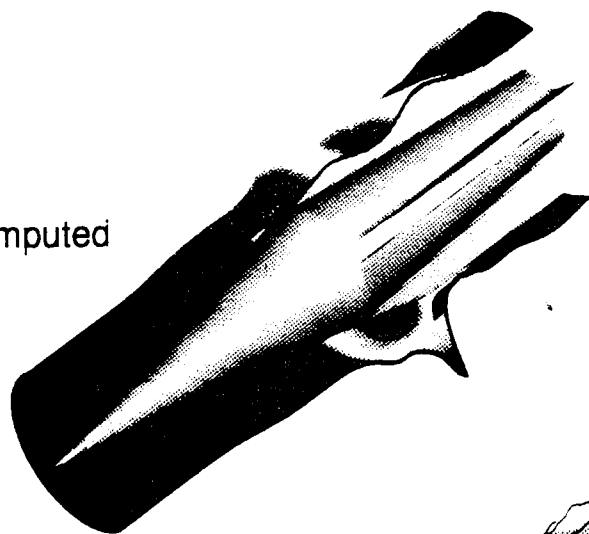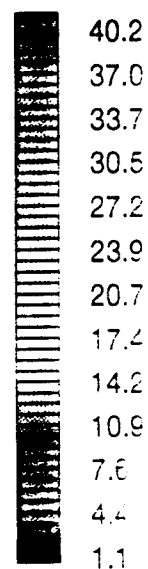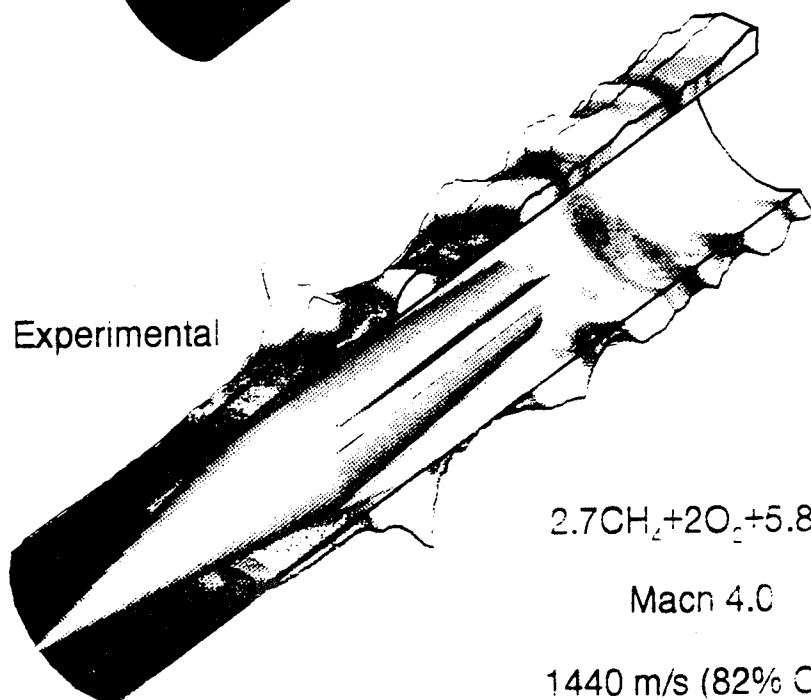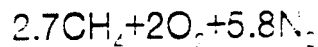
Mach 4.0

1440 m/s (82% C-J)

Pressure Ratio
16.1
14.9
13.6
12.3
11.0
9.8
8.5
7.2
5.9
4.7
3.4
2.1
0.9

Pressure Ratio
40.2
37.0
33.7
30.5
27.2
23.9
20.7
17.4
14.2
10.9
7.6
4.4
1.1

Pressure History of the Ram Accelerator

HS 044

$2O_2$, $2.7CH_4$, $5.8N_2$, 30 atm

5 Fin Mg Body/Al Nose

Pressure (normalized)

Distance Down Tube (m)

$V_{in} = 1170$ m/s

$V_{final} \sim 2180$ m/s

Position (mm)

PRESSURE TRANSDUCER 4.585m from R.F.T. in a 120-mm GUN

PRECURSOR AND OVERSHOOT

BEGINNING OF EVIDENCE OF STRESS INDUCED GAGE MALFUNCTION

TIME

25.0ms

22.5ms

20.0ms

300.0

200.0

100.0

0.0

112

FFT OF SIGNAL FROM PRESSURE TRANSDUCER 4.585m from R.F.T.
IN A 120-mm GUN

GAGE RESONANCE

HIGHER DOMINANT
FREQUENCIES
PRESUMABLY ASSOCIATED
WITH GAGE RESONANCE
AND CAVITY DESIGN

FREQUENCY

50.0khz   100.0khz   150.0khz   200.0khz   250.0khz

1.5E-4

1.0E-4

5.0E-5

0.0
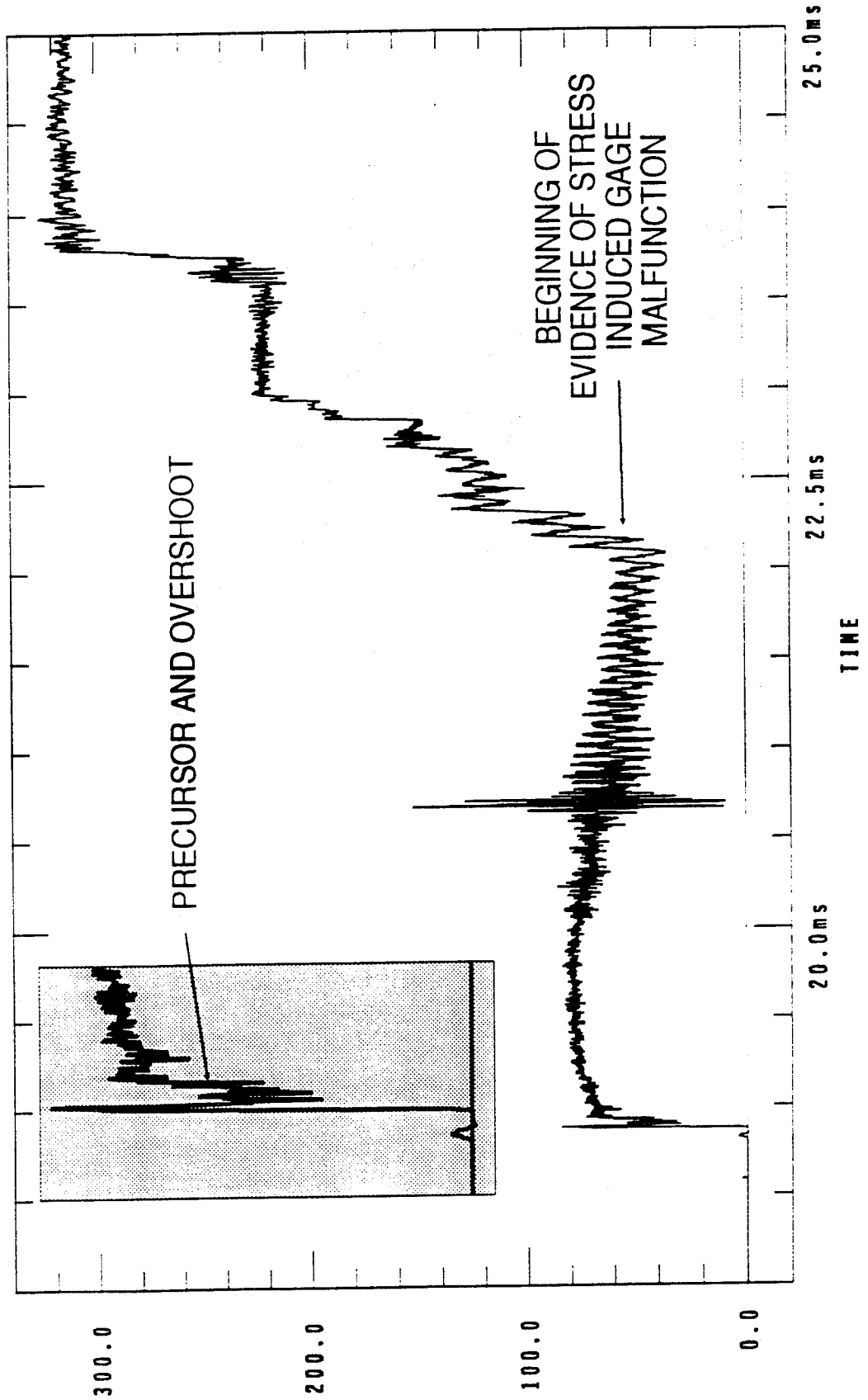
STRAIN TRANSDUCER (hoop) 5.525m from R.F.T. in a 120-mm GUN
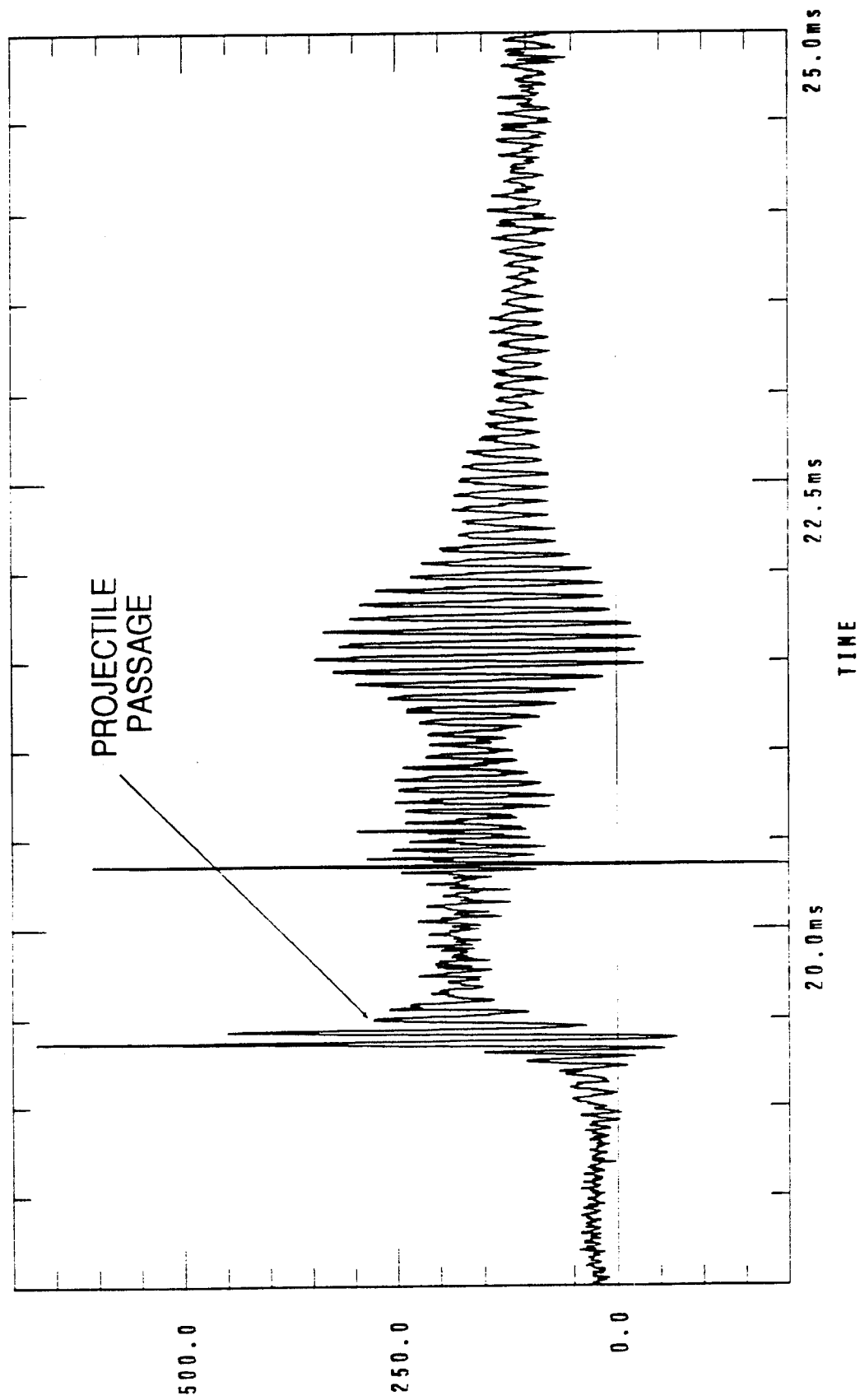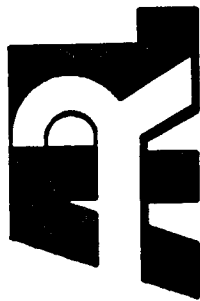
FFT OF SIGNAL FROM STRAIN TRANSDUCER 5.525m from R.F.T. IN A 120-mm GUN
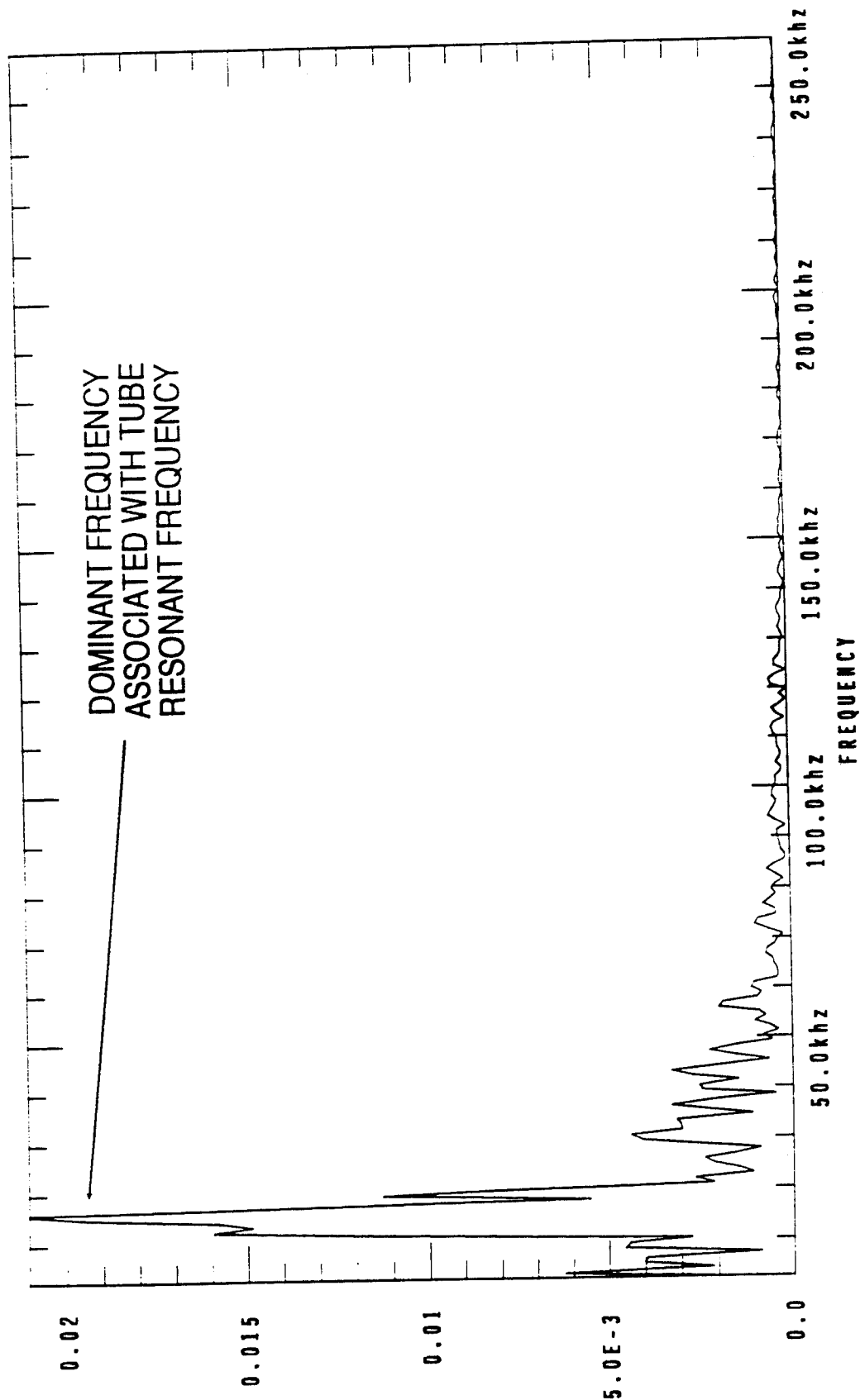
DOMINANT FREQUENCY ASSOCIATED WITH TUBE RESONANT FREQUENCY

FREQUENCY

PRESSURE TRANSDUCER IN POSITION ONE OF HIRAM
ACCELERATOR SECTION ONE

PROJECTILE &
SHOCK FRONT
PASSAGE

NEGATIVE EXCURSION
DUE TO SETTING OF
BASELINE AT
PREPRESSURIZATION
LEVEL

200.0

150.0

100.0

50.0

0.0

-50.0

20.0ms   25.0ms   30.0ms   35.0ms

TIME

116

FFT OF SIGNAL FROM PRESSURE TRANSDUCER IN POSITION ONE
OF HIRAM ACCELERATOR SECTION ONE

DOMINANT FREQUENCIES FROM THE HIGHER
RANGE ASSOCIATED WITH GAGE RESONANCE
AND CAVITY DESIGN AND A WIDE LOW
FREQUENCY BAND NOT SEEN IN THE
STANDARD GUN DATA (HIRAM COMBUSTION?)

GAGE RESONANCE

1.5E-3

1.0E-3

5.0E-4

0.0

50.0khz   100.0khz   150.0khz   200.0khz   250.0khz

FREQUENCY

117

CROSS POWER SPECTRUM BETWEEN GUN MOUNTED PRESSURE
TRANSDUCER AND GUN MOUNTED STRAIN GAGE

AGREEMENT AT LOW
FREQUENCIES WHERE
GUN RESONANCE IS
VERY STRONG
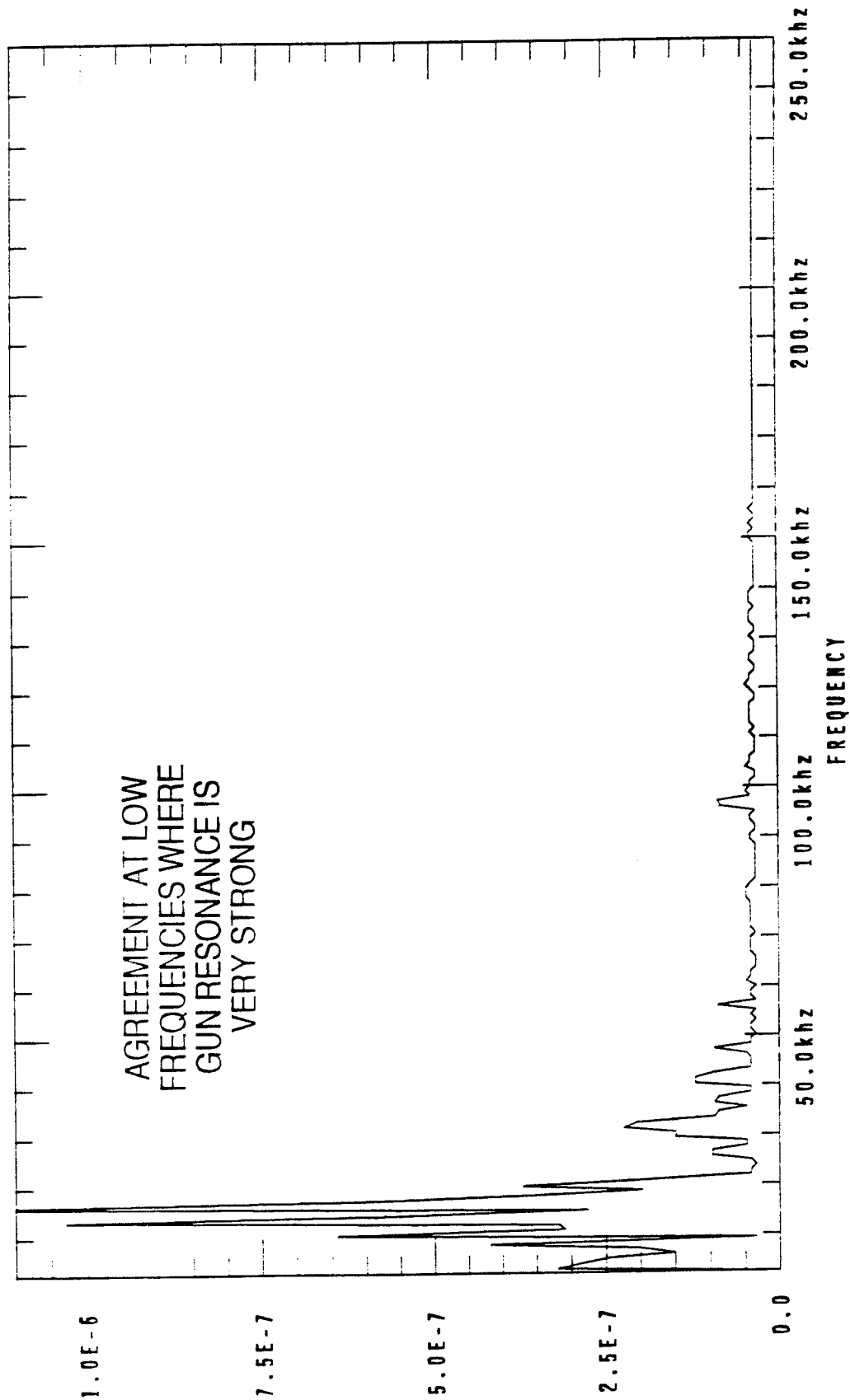
CROSS POWER SPECTRUM BETWEEN GUN MOUNTED PRESSURE
TRANSDUCER AND HIRAM PRESSURE TRANSDUCER

AGREEMENT MAINLY
AT HIGHER
FREQUENCIES
ASSOCIATED WITH
TRANSDUCERS AND
GAGE CAVITIES

SOME AGREEMENT
AT LOWER
FREQUENCIES
ASSOCIATED WITH
COMBUSTION

1.5E-7

1.0E-7

5.0E-8

0.0   50.0khz   100.0khz   150.0khz   200.0khz   250.0khz

FREQUENCY
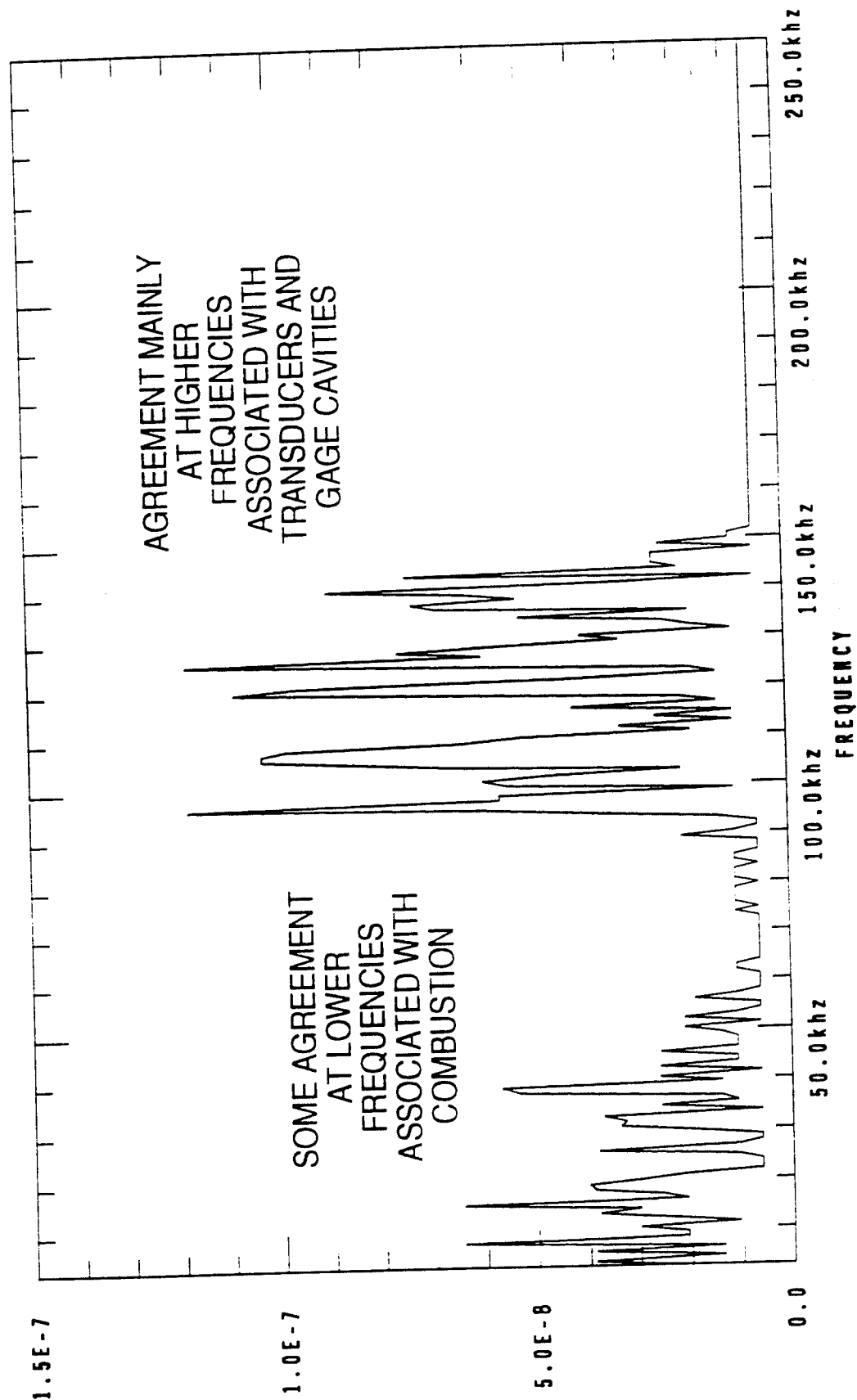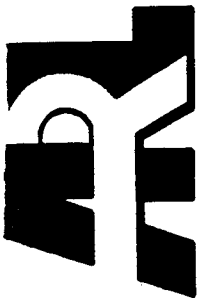
CROSS POWER SPECTRUM BETWEEN GUN MOUNTED STRAIN GAGE AND HIRAM PRESSURE TRANSDUCER

AGREEMENT AT LOW FREQUENCIES WHERE GUN RESONANCE IS VERY STRONG
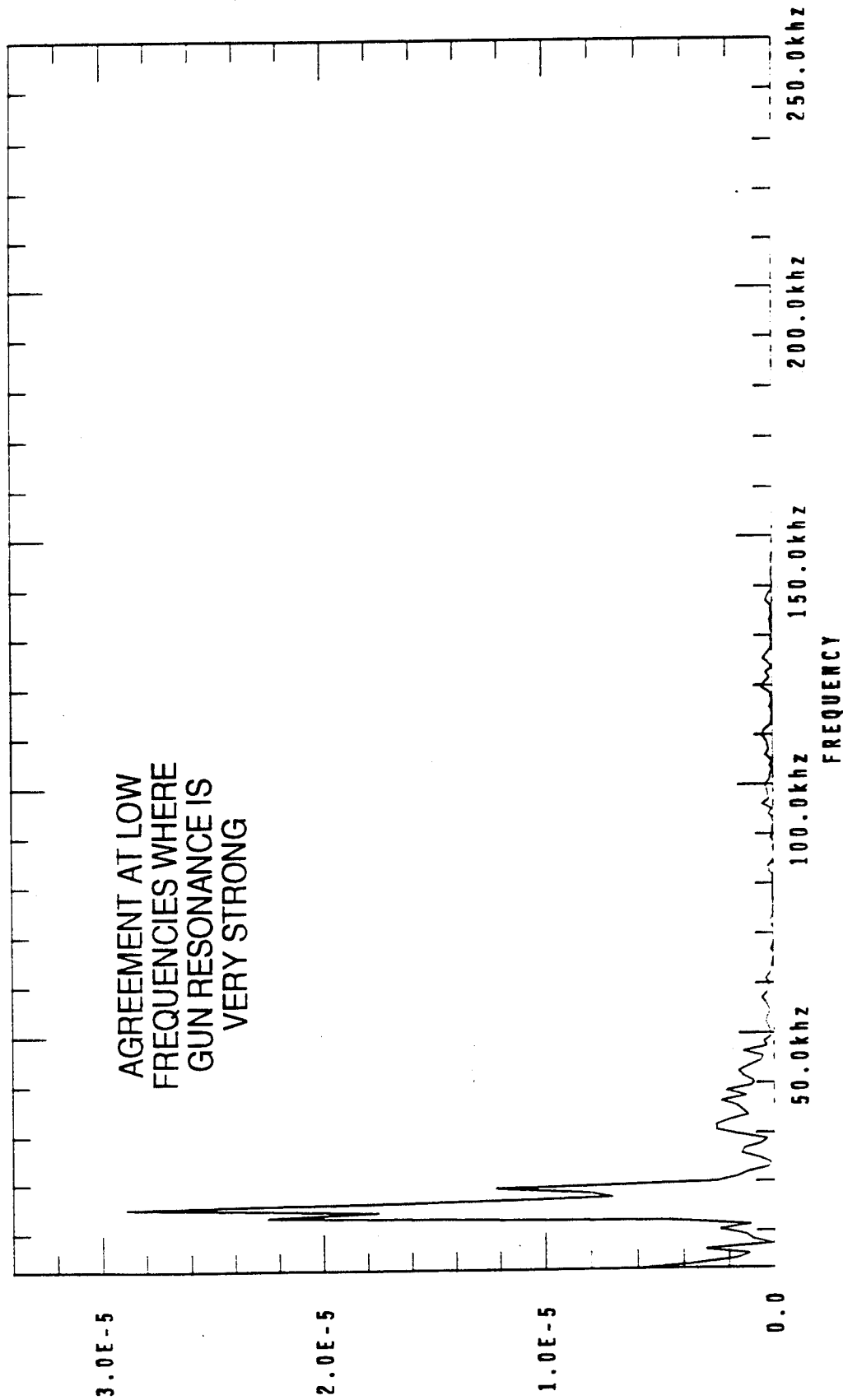
PRESSURE RECORD FROM HIRAM PROJECTILE PASSAGE IN 1000psi N₂, "STEPPED" GAGE PORT
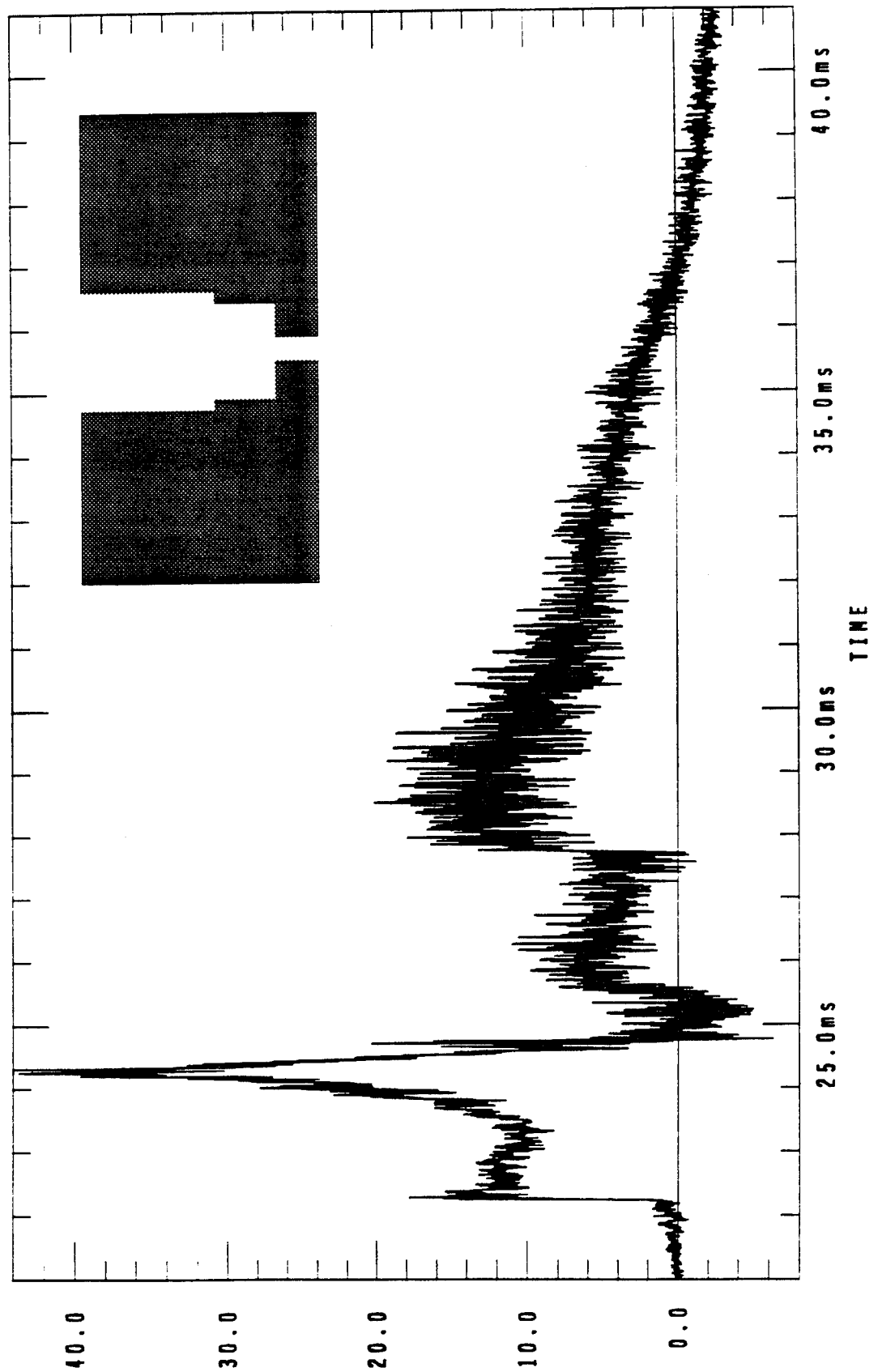
PRESSURE RECORD FROM HIRAM PROJECTILE PASSAGE IN
1000psi N₂, "THROUGH" GAGE PORT
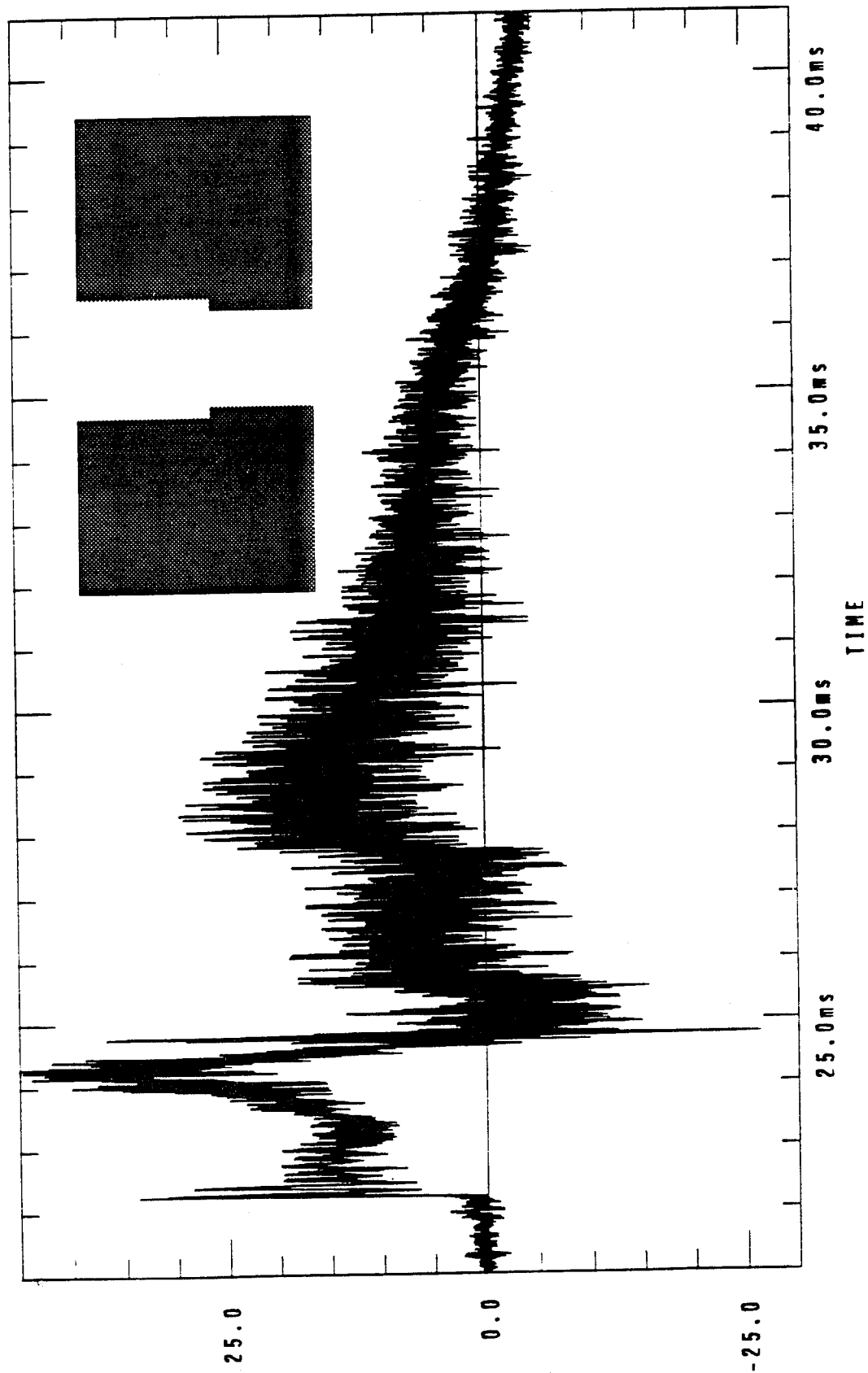
FFT OF PRESSURE RECORD FROM HIRAM PROJECTILE PASSAGE
IN 1000psi N₂, "STEPPED" GAGE PORT
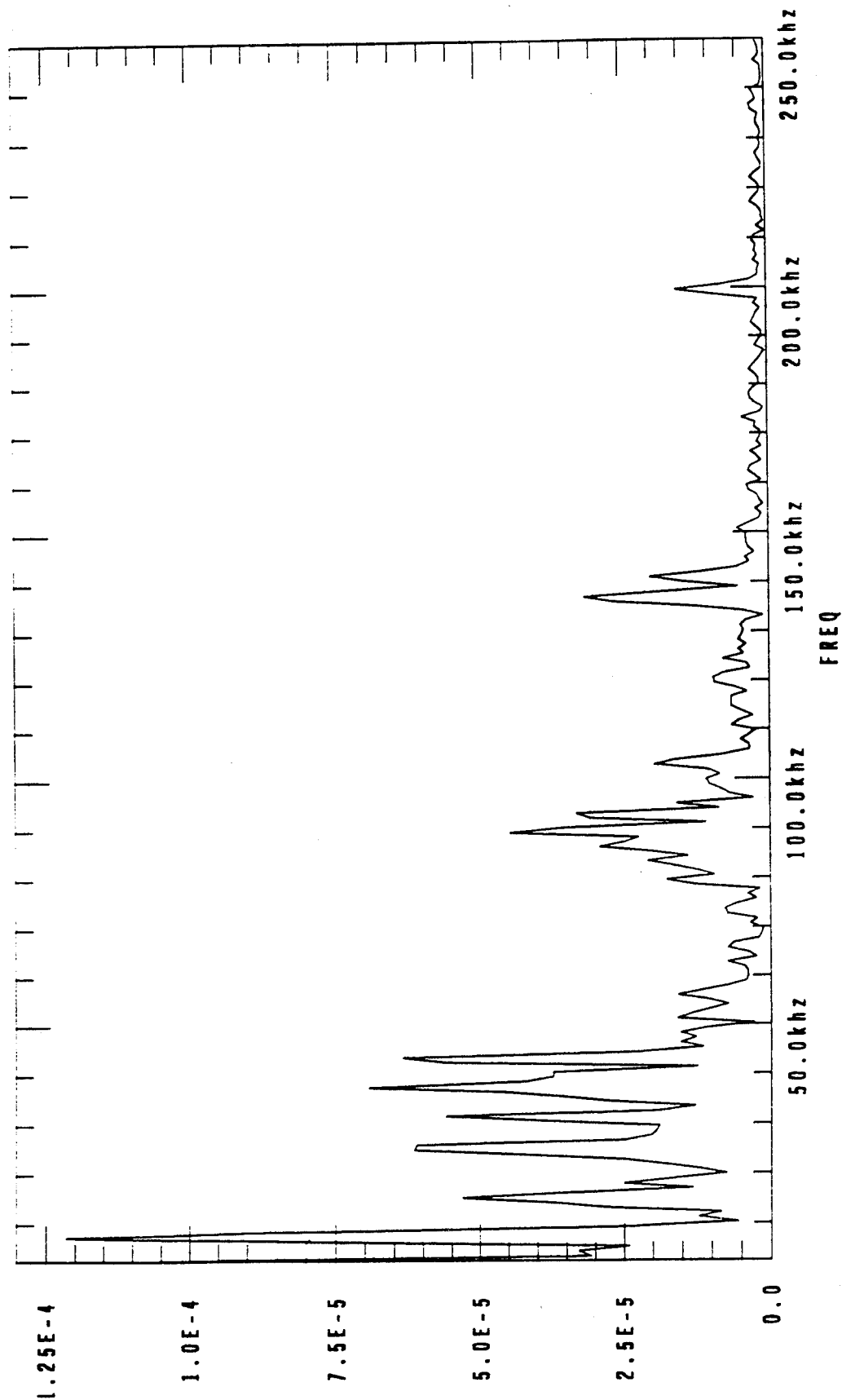
FFT OF PRESSURE RECORD FROM HIRAM PROJECTILE PASSAGE
IN 1000psi N₂, "THROUGH" GAGE PORT
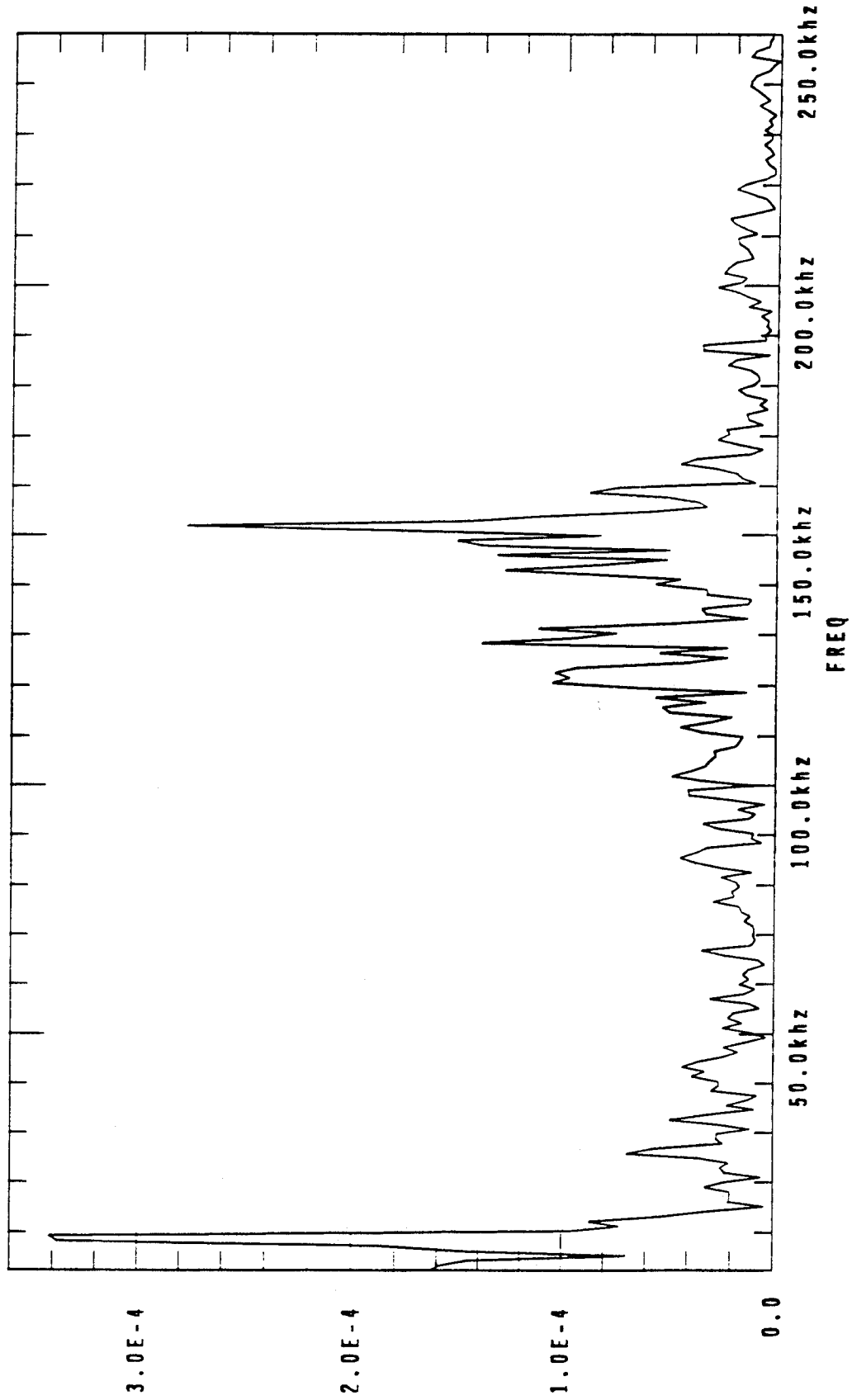
"STEPPED" PORT AND "THROUGH" PORT FFT's

250.0khz

200.0khz

"THROUGH" PORT
SHOWS MUCH
GREATER
RESPONSE AT
HIGHER
FREQUENCIES

150.0khz

FREQ

100.0khz

SOME AGREEMENT
AT LOWER
FREQUENCIES

50.0khz

—— "STEPPED" PORT

—— "THROUGH" PORT

3.0E-4

2.0E-4

1.0E-4

0.0
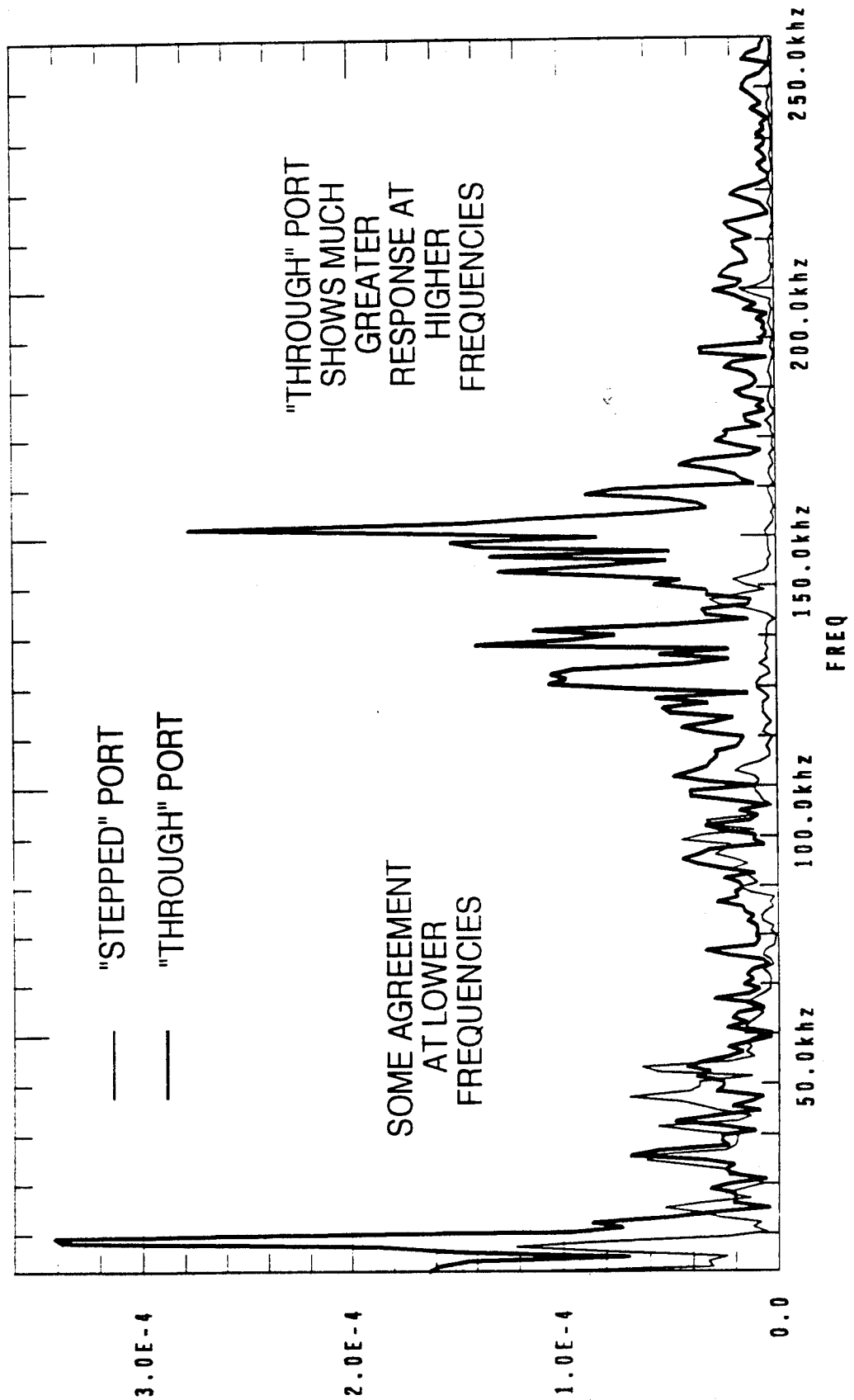
CONCLUSIONS

- LOW FREQUENCY SIGNALS (20kHz - 50kHz), POSSIBLY ASSOCIATED WITH THE INBORE RAMJET COMBUSTION PROCESS, ARE PRESENT IN HIRAM PRESSURE DATA

- "THROUGH" PRESSURE GAGE PORT ALLOWS TRANSMISSION OF HIGH FREQUENCIES FILTERED OUT BY A "STEPPED" PORT

FUTURE WORK/DIRECTIONS

- STRAIN INSTRUMENTATION ON HIRAM TUBES

- TELEMETRY IN HIRAM ENVIRONMENT

- CORE FLOW PRESSURE TRANSDUCER

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APPENDIX F:

PRESENTATION - "AN OPTICAL PRESSURE GAUGE FOR HIGH SPEED MEASUREMENTS IN THE 10-250 KBAR RANGE"

This Appendix is presented in its original form without editorial changes or comments.

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AERODYNE RESEARCH, INC.

AN OPTICAL PRESSURE GAUGE FOR HIGH SPEED MEASUREMENTS IN THE 10-250Kbar RANGE

J. WORMHOUDT, P.L. KEBABIAN, AND K.D. ANNEN

AERODYNE RESEARCH, INC.
CENTER FOR CHEMICAL AND ENVIRONMENTAL PHYSICS

45 Manning Road
Billerica. MA 01821-3976
(508) 663-9500   Fax (508) 663-4918

131

Objective: A Diagnostic for Underwater Detonations

- Typical charge: 1 pound pentolite sphere

- Maximum pressure: p_{max} up to 250 kbar

- Measurement duration to 1/e of p_{max} (<50 μs)

- Time resolution consistent with shock duration (0.1 μs at p_{max}>100 kbar)

- Minimal temperature sensitivity
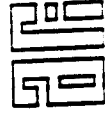
Selected Approach: Fluorescence of Ruby (Al_2O_3:$Cr+3$)

Advantages:

- Well established technique, widely used in diamond anvil cells, also demonstrated for shock sensing
- Optical— not bothered by electromagnetic effects
- Fiber optic coupling to remotely located analysis/recording
- Ruby crystals cheap, readily available

Challenges:

- Prior high speed work required Ar+ laser for excitation, and spectrograph with intensified streak camera for analysis— expensive, difficult to field
- Ruby is temperature sensitive, ~5 °C ‹—› 1 kbar

Nondispersive Wavelength Analysis

- Ruby R lines at p=0, R_1 at 694.3 and R_2 at 692.9 nm

- $d\lambda/dp = 3.6 \times 10^{-2}$ nm/kbar, $\Delta\lambda_{max} = 9$ nm

- RG695 glass exhibits rapid increase of transmission with λ at these wavelengths

- So, measure transmission of filter glass relative to transmission at p=0

- Simple and economical to implement— no spectrograph or streak tube

134

Wavelength Analyzer and Test Probe

Fiber from Excitation Source

L1
F1
F3
F2
Fiber to Sensor
L2
D1
L3
Beam Splitter
F4
Heater
L4
D2

SMA Fiber Connector
Ruby Crystal
Aluminized Mylar
Stainless Steel
Torr-Seal Epoxy
Fiber
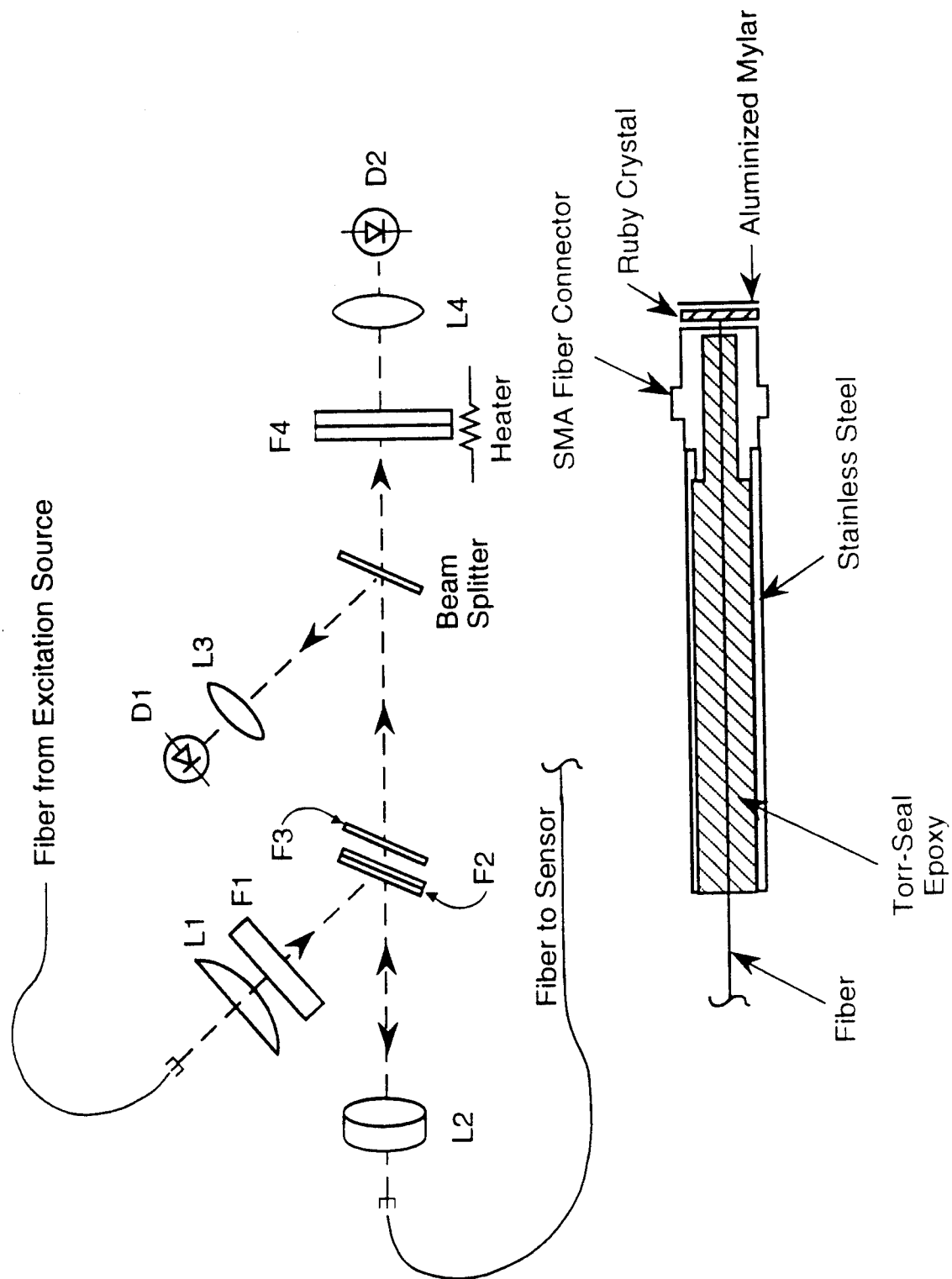
Key to Wavelength Analyzer Optical Layout Schematic

L1 collimates light from excitation source

F1 removes all red light from excitation

F2, interference filter, reflects blue pump light, transmits returning red fluorescence

F3, red filter, suppresses scattered pump light

Beamsplitter reflects ~20 per cent

D1/L3, reference detector, signal proportional to total fluorescence, ~independent of $\Delta\lambda$

F4, RG695 glass filter

D2/L4, signal detector— spectrally selective, due to F4 in beam

136

Signal Processing

- At p=0, adjust R1 to null difference output

- At p>0, D2 signal increases relative to D1, so difference output increases

- Record difference and reference (D1) signals on storage scope

- Normalize difference signal by D1 signal

(by computer, or by analog divider circuit)
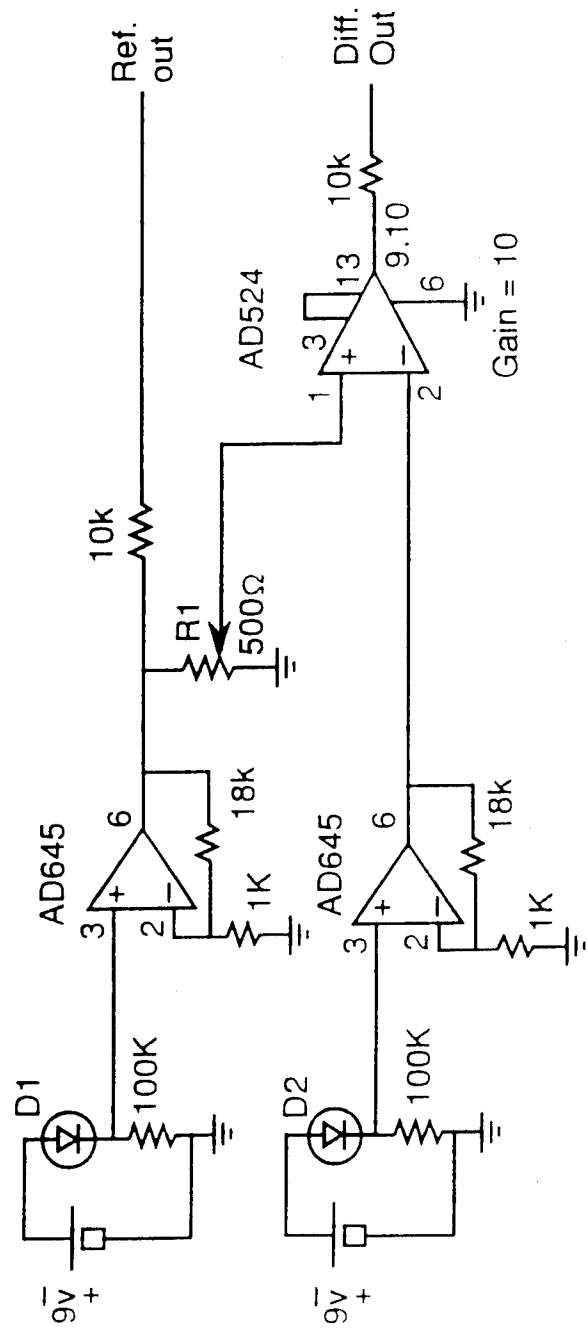
Transmission of RG695 Glass
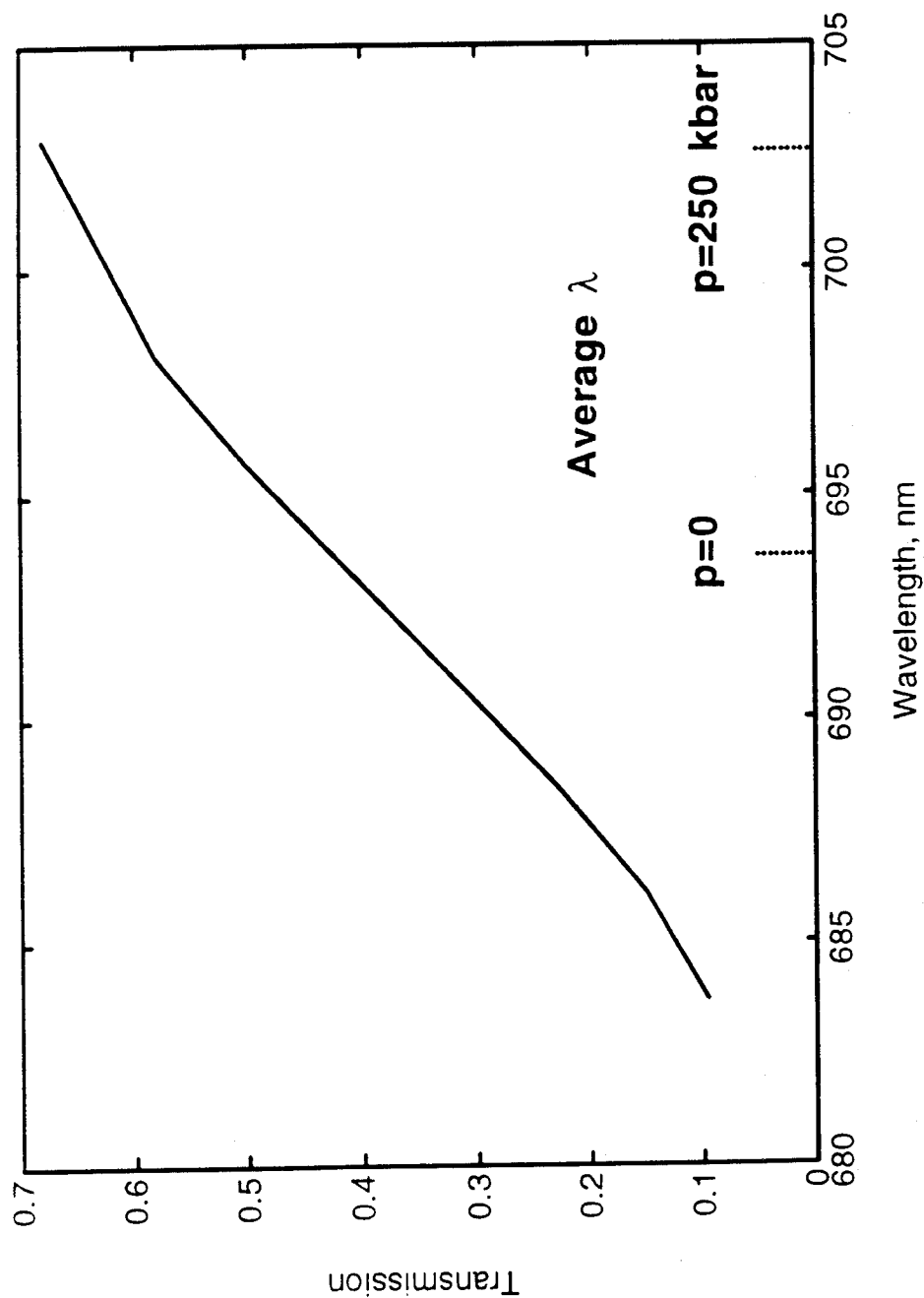
Region of maximum change in transmission
coincides with $\Delta\lambda \leq$ 9nm fluorescence shift

Pump Ruby by Flashlamp-Excited Plastic Optical Fiber Containing Fluorescent Dye

Motivation: Ruby stores pump energy during ~3 ms fluorescence lifetime, much longer than desired measurement duration, so don't need cw source (laser)

Advantages:

- Both flashlamp and fiber are very cheap

- Spectrum of dye is well matched to ruby excitation spectrum

- Higher power density— exceeds that of arc in flash lamp

Achieved in Phase I:

- 20 mJ (9 W peak) from 1 mm fiber, NA=0.6

- 0.04 mJ (18 mW peak) into 200 μm, NA=0.25 fiber

- Concentration ratio 5X

- Geometrical optics will allow up to 3.5X increased power into 200 μm fiber

Temperature Effects

- Broadband optical system results in lower temperature sensitivity than spectrograph observing only R lines

- Compressional heating of crystal is insignificant

- Conductive heating small enough to be corrected iteratively with thermal model of gauge

- Literature suggests $SrB_4O_7:Sm^{+2}$ is a suitable alternative with much smaller temperature sensitivity

MECHANICAL LOADING TEST OF SENSOR RESPONSE TO APPLIED FORCE

SMA Connector used as Piston

Ruby Ball, 0.1250" diam.

SMA Fiber Bulkhead Union

Applied Force

0.0005" Alum. Foil

Ruby Sensor Crystal

Fiber SMA Connector

Fiber to Wavelength Analyser

Change in Filter Transmission, Per Cent
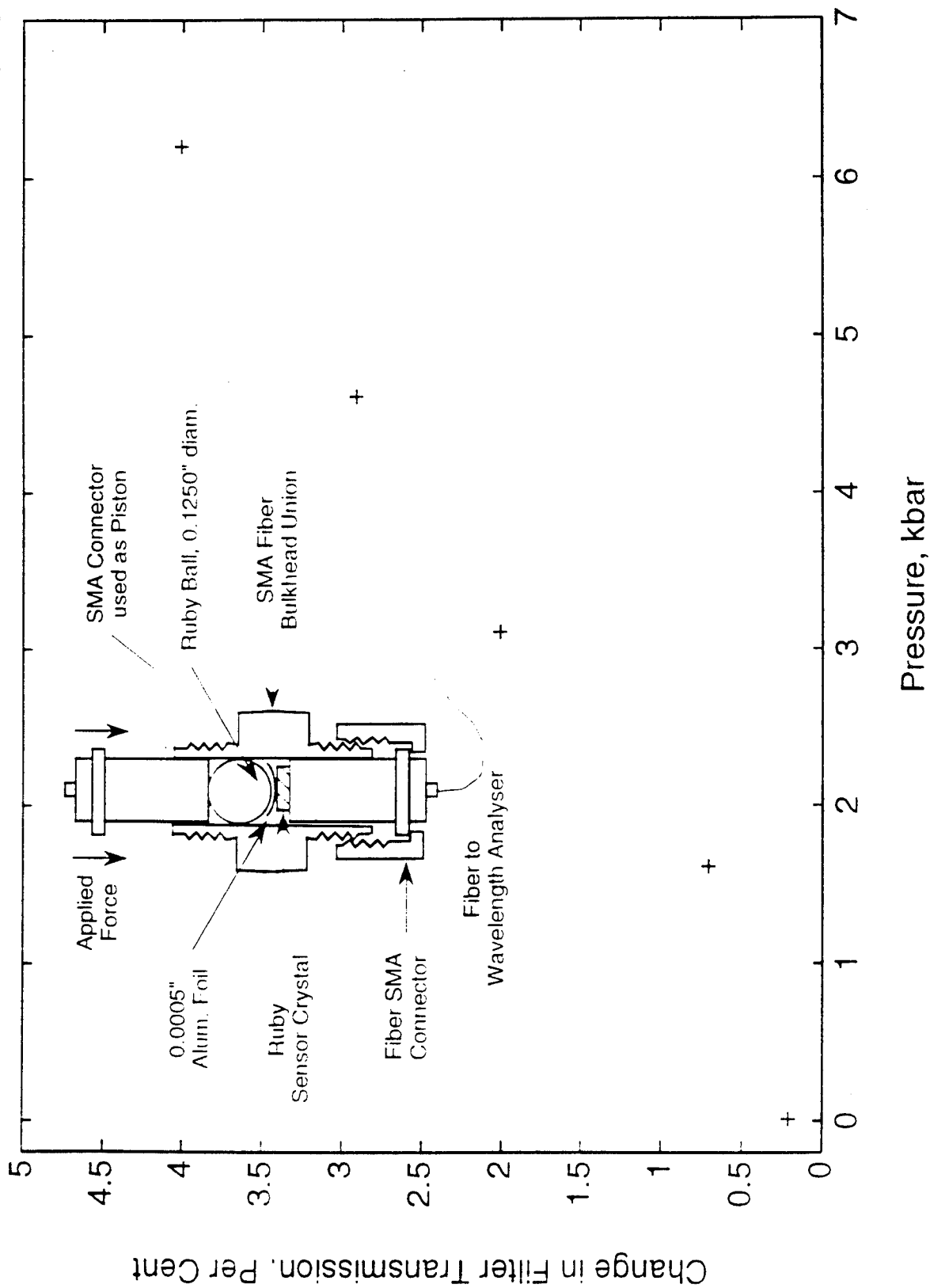
Pressure, kbar

Issues in Using This Technique for Gun Measurements

- Enhanced sensitivity in relevant pressure range below 10 kbar

- Measurement duration up to 25 ms

- Thermal design

- Achieving flat frequency response

- Mechanical interchangability with existing gauges

142

Modifications in the Technique for Gun Measurements

- Enhanced sensitivity: Use second ruby crystal as detector filter

- Measurement duration: Use longer flash

- Thermal design: Add cover plate over sensor crystal, to provide thermal lag time of > 25 ms

- Frequency response: Avoid resonances by using crystals in close acoustic contact to structure

- Mechanical interface:

- Reflective coatings reduce both stray light and radiative heating

- Sensor body would be mechanically similar to currently used gauges

- Fiber losses not severe at up to 100 m fiber length

Small Shifts in the Fluorescence Wavelength Observed by Changes in Transmission Through a Second Crystal

(A) Fluorescence Spectrum

(B) Filter transmission

(C) Transmitted spectrum

(D) Transmitted Flux vs. dλ

144
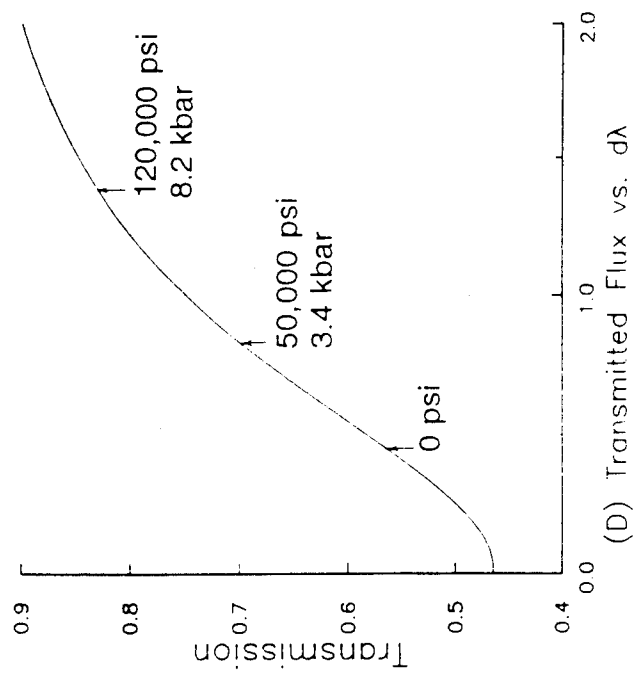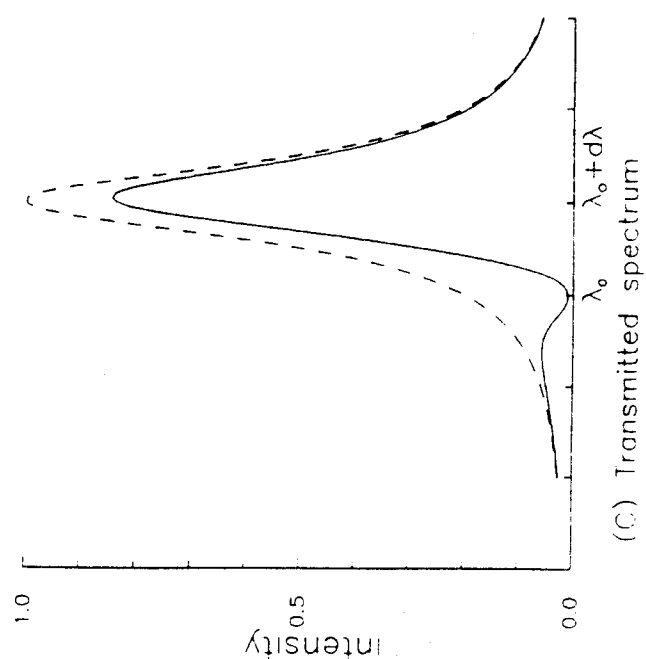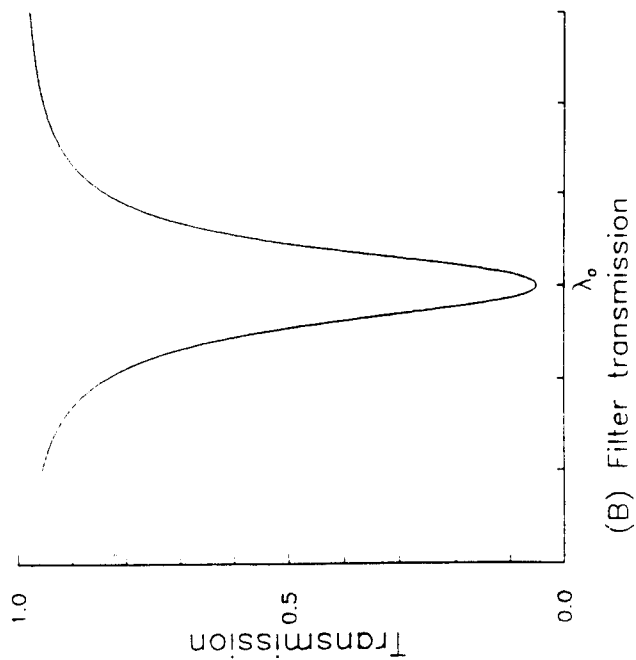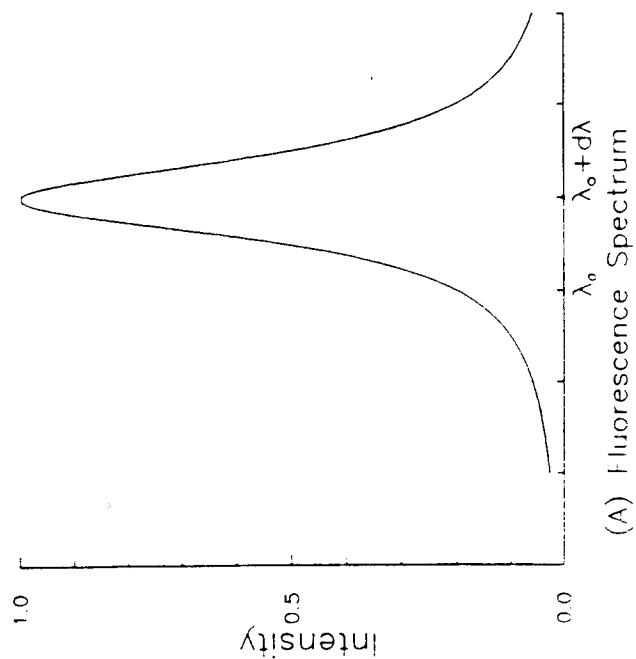
Schematic of Modified Sensor for Gun Measurements

Buffer Plate

Retainer Cap

Retaining Epoxy

Sensor Crystal

Reflecting Film

Sealing Shoulder

M 10 X 1 Thread

Optical Fiber
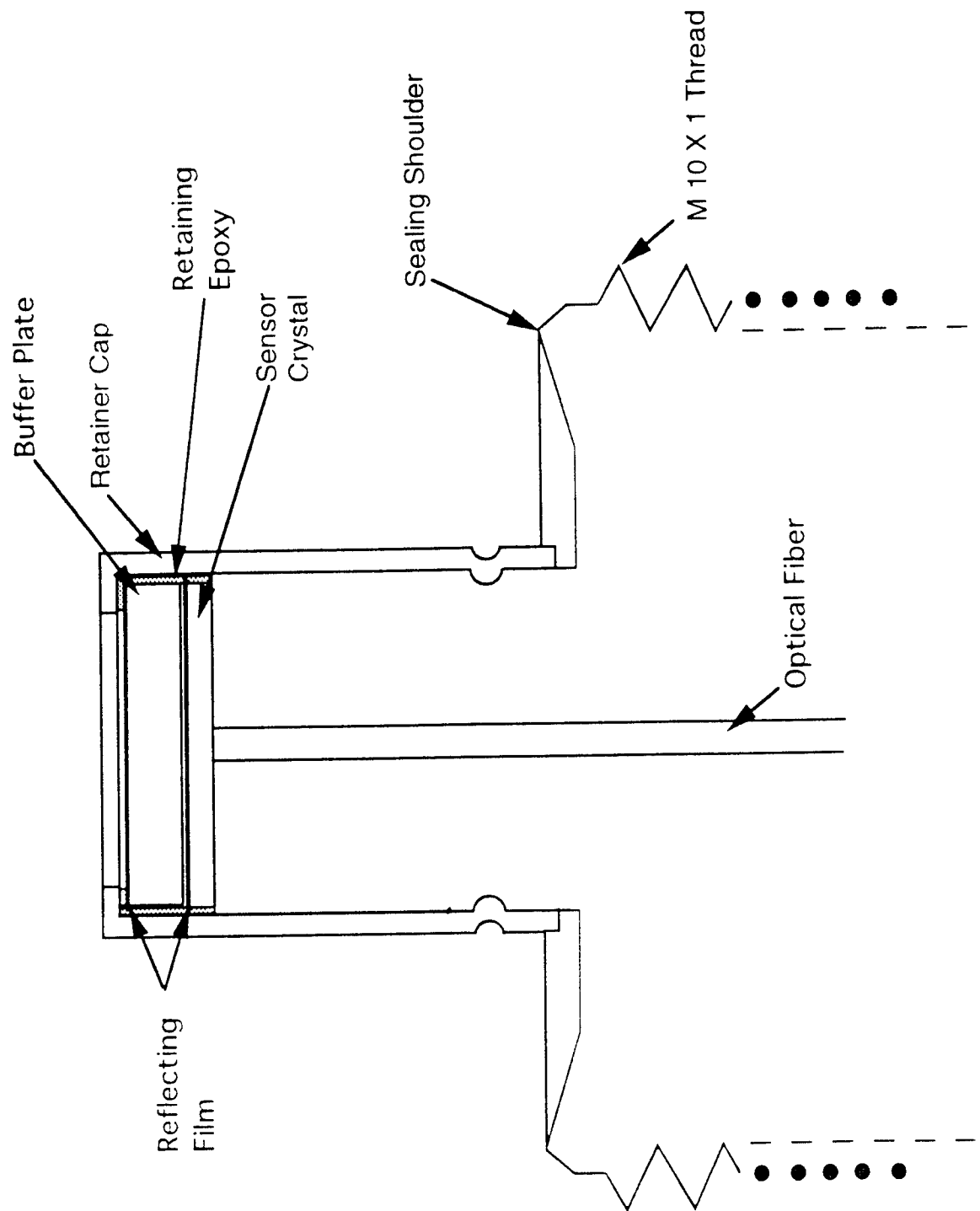
Conclusions

- The Aerodyne shock pressure sensor will be a simple and cost effective way to measure shock pressures in the 100 kbar range

- Simple changes would allow it to be used for gun tube pressure measurements

Acknowledgment

Phase I SBIR, Naval Surface Warfare Center

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APPENDIX G:

PRESENTATION - "PRESSURE TRANSDUCERS FOR THE LIQUID PROPELLANT GUN"

This Appendix is presented in its original form without editorial changes or comments.

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PRESSURE SEAL WASHER

NEG. CHARGE COLLECTOR

TOURMALINE CRYSTAL

RETAINER CAP

POS. CHARGE COLLECTOR

INSULATING EPOXY

INSULATING WASHER

CRYSTAL BASE

PRESSURE SEAL WASHER

TRANSDUCER BODY
3/8-24 NF THREADS

INSULATED CONDUCTORS

MICRODOT CONNECTOR

INSULATING SLEEVE
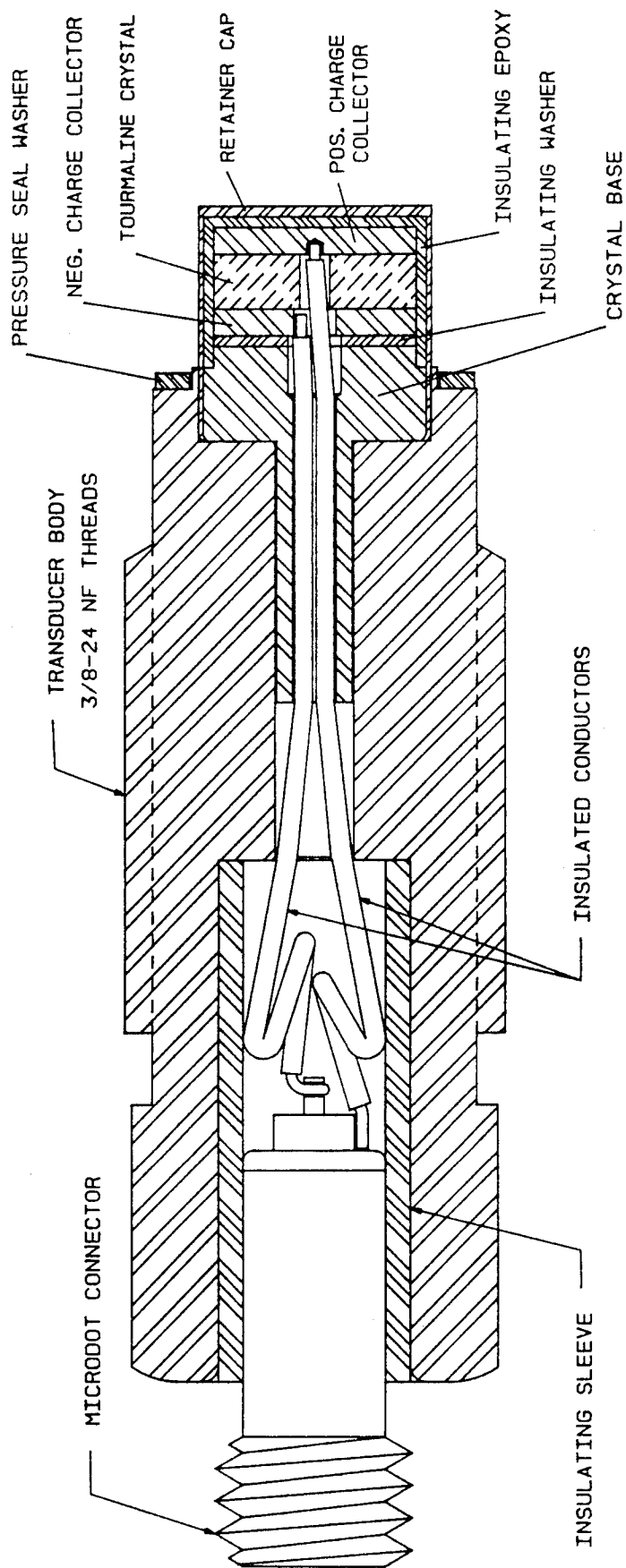
PRESSURE RANGE: 110,000 PSI

OUTPUT SENSITIVITY: 0.33 PICOCOULOMBS/PSI

UNIQUE FEATURE: PRESSURE SENSING ELEMENT IS ELECTRICALLY INSULATED FROM GROUND.

PROBLEMS ASSOCIATED WITH LIQUID PROPELLANT APPLICATION:

1. MICRODOT CABLE CONNECTOR LOOSE AFTER EACH ROUND.
2. TRANSDUCER MICRODOT CONNECTOR FREQUENTLY DAMAGED
   IN MORE SEVERE APPLICATIONS.
3. TRANSDUCER LOOSE IN MOUNTING HOLE AFTER EACH ROUND.
4. TRANSDUCER HAD TO BE REMOVED AND SERVICED AFTER EACH ROUND.
5. PRESSURE SEAL WASHER DIFFICULT TO REMOVE FROM GAGE HOLE.

YUMA PROVING GROUND MODEL E30MP PRESSURE TRANSDUCER

151

PRESSURE RANGE: 100,000 PSI
OUTPUT SENSITIVITY: 0.33 PICOCOULOMBS/PSI
SENSING ELEMENT ELECTRICALLY INSULATED FROM GROUND

METAL DISC
.005" SS SHIM STOCK

TEFLON CUP

PRESSURE SENSING ELEMENT

THERMAL SHIELD CAP

PRESSURE SEAL WASHER

14X1.25 MM

TEFLON INSULATING SLEEVE

.24

1.66
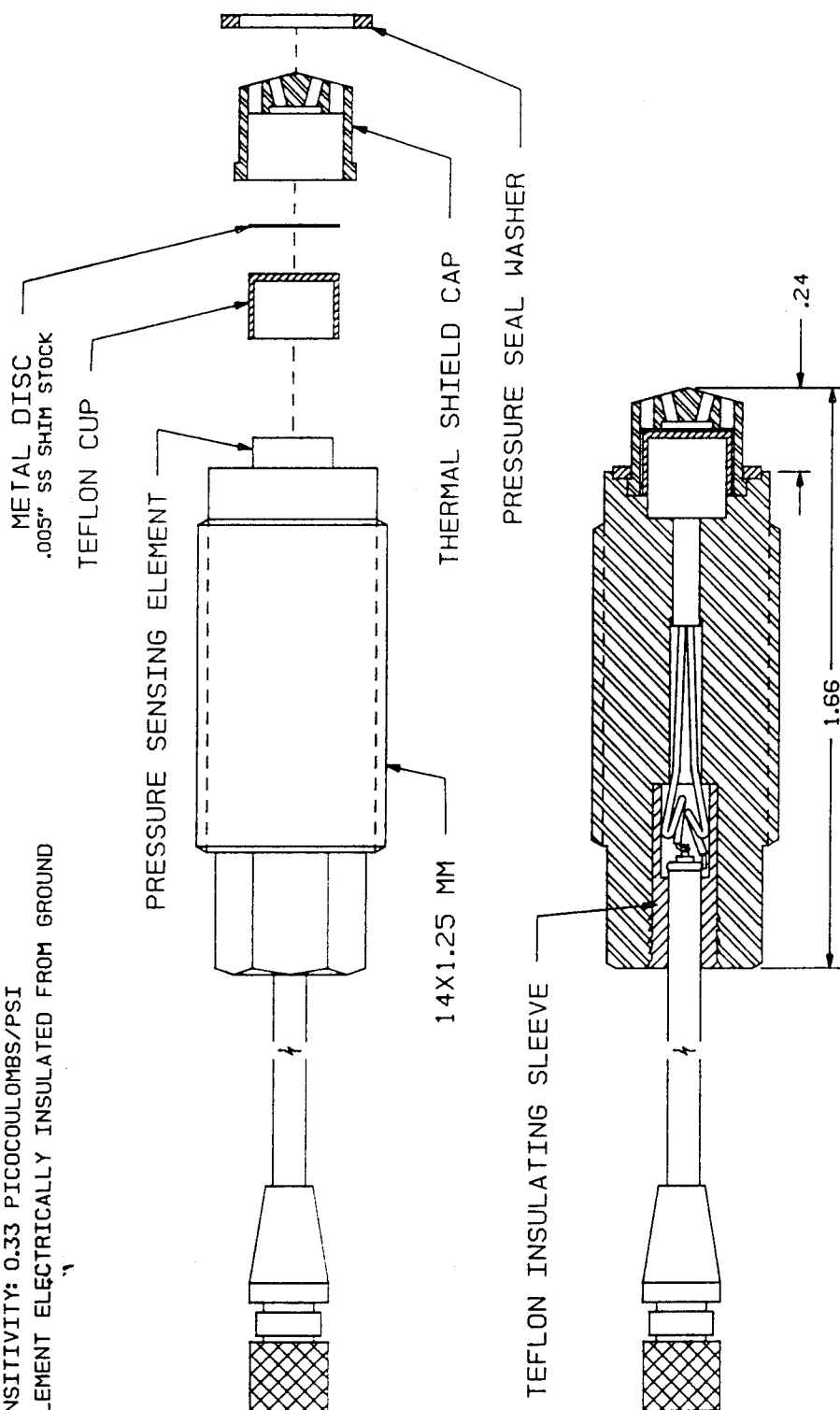
IMPROVEMENTS OVER E30MP TRANSDUCER FOR LIQUID PROPELLANT APPLLICATIONS:

1. HAS COAX CABLE PIGTAIL INSTEAD OF STANDARD MICRODOT CONNECTOR.

2. MOUNTING TORQUE IS HIGH (90 FT-LBS) WHICH REDUCES THE POSSIBILITY OF THE TRANSDUCER WORKING LOOSE AND CAUSING BLOW-BY.

3. PRESSURE SEAL WASHER REMAINES ATTACHED TO THE TRANSDUCER.

4. HAS BUILT-IN THERMAL PROTECTION SYSTEM.

YUMA PROVING GROUND MODEL E30FM PRESSURE TRANSDUCER

152

NOTES:

1. APPLICABLE STANDARDS/SPECIFICATIONS:
   A. DOD-STD-00100(DAR)
   B. ANSI Y14.5M - 1982

2. MATERIAL: STEEL, MARAGING, SPEC MIL-S-46850C, GRADE 300.

3. HEAT TREATMENT:

4. UNLESS OTHERWISE SPECIFIED: ALL SURFACES 32 MICROINCHES.

5. REFERENCE DRAWING NO. 93025-2, SHEET 2 OF 2, FOR FINISH MACHINING AFTER HEAT TREAT.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE (YR-MO-DA)	APPROVED

R .075

R .130

ø .0350 (#65 DRILL)
(8 HOLES)

ø .040 (#60 DRILL)
(12 HOLES)

SECTION A-A

ø .320 ±.001

.240 ±.001

45°X.005

ø .2680 ±.0005

ø .349/.348

.18 ±.01

.255 ±.001

.280 ±.001

PART NO. 93025-2

U.S. ARMY YUMA PROVING GROUND
YUMA, ARIZONA 85365

MODEL E30MT3M PRESSURE TRANSDUCER

THERMAL SHIELD

BEFORE HEAT TREAT

SIZE	CAGE CODE	DWG NO.	93025-2
A			

SCALE 8/1 | UNIT WT | SHEET 1 OF 2

CONTRACT NUMBER		
CONTRACTOR		
DRAWN BY H.E. PHILLIPS	DATE (YR-MO-DA) 83-02-01	
CHECKER	ENGINEER H.E. PHILLIPS	
DRAWING APPROVAL		
DESIGN APPROVAL		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES
DECIMAL: 0.001
FRACTIONAL: ± 1/64
ANGULAR: ± 0.5°

MECHANICAL PROPERTIES	PMIC		
YP			
TS			
EL2			
RA			
BH			
	NEXT ASSY	USED ON	MATL ENGR
RH	C 52 MIN.		
	APPLICATION		

NOTES:

1. APPLICABLE STANDARDS/SPECIFICATIONS:
   A. DOD-STD-00100D(AR)
   B. ANSI Y14.5M - 1982

2. MATERIAL: STEEL, MARAGING, SPEC MIL-S-46850C, GRADE 300.

3. HEAT TREATMENT:

4. UNLESS OTHERWISE SPECIFIED ALL SURFACES 32 MICROINCHES.

5. REFERENCE DRAWING NO. 93025-2, SHEET 2 OF 2, FOR FINISH MACHINING AFTER HEAT TREAT.

R .075

R .040

R .130

∅ .0312 (1/32 DRILL) (4 HOLES)

∅ .0350 (#65 DRILL) (8 HOLES)

∅ .040 (#60 DRILL) (12 HOLES)

A — A

∅ .320 ±.001

.240 ±.001

.18 ±.01

.255 ±.001

.280 ±.001

45°×.005

∅ .2680 ±.0005

∅ .349/.348

SECTION A-A

PART NO. 93025-2

REVISIONS			
ZONE	REV	DESCRIPTION	DATE (YR-MO-DA)	APPROVED

MECHANICAL PROPERTIES	PMIC		
YP			
TS			
EL2			
RA			
BH		NEXT ASSY	USED ON
RH	C 52 MIN.	APPLICATION	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES	CONTRACT NUMBER	
TOLERANCES	CONTRACTOR	
DECIMAL: 0.001		
FRACTIONAL: ± 1/64	DRAWN BY W.E. PHILLIPS	DATE (YR-MO-DA) 93-03-01
ANGULAR: ± 0.5°	CHECKER	ENGINEER W.E. PHILLIPS
	DRAWING APPROVAL	
MATL ENGR	DESIGN APPROVAL	

U.S. ARMY YUMA PROVING GROUND
YUMA, ARIZONA 85365

MODEL E30MT3M PRESSURE TRANSDUCER
THERMAL SHIELD - 24 HOLE
BEFORE HEAT TREAT

SIZE A	CAGE CODE	DRWG NO. 93060-1	
SCALE 8/1	UNIT WT		SHEET 1 OF 2

VG #8

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
   A. DOD-STD-OO100(IAR)
   B. ANSI Y14.5M - 1982
2. MATERIAL: STEEL, MARAGING, SPEC MIL-S-46850C, GRADE 300.

$\varnothing$ .3500
$\varnothing$ .325 ±.001

A

A

$\varnothing$ .035 (#65 DRILL)
6 HOLES EVENLY SPACED

$\varnothing$ .040 (#60 DRILL)
12 HOLES EVENLY SPACED
AT .120 RADIUS

.065

15°

$\varnothing$ .150 ±.003

.190 ±.001

.190 ±.001
.210 ±.003
.305 ±.003

$\varnothing$ .280 ±.001

.050 ±.001

PART NO.

SIZE A	CAGE CODE	DWG NO. 93259-1
SCALE 8/1	UNIT WT	SHEET 1 OF 1

CONTRACT NUMBER

CONTRACTOR

	DATE (YR-MO-DA)
DRAWN BY W.E. PHILLIPS	93-09-16
CHECKER	ENGINEER W.E. PHILLIPS
DRAWING APPROVAL	
DESIGN APPROVAL	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES
DECIMAL: 0.001
FRACTIONAL: ± 1/64
ANGULAR: ± 0.5°

MECHANICAL PROPERTIES	PMIC
YP	
TS	
EL2	
RA	
BH	
RH	C 52 MIN.

NEXT ASSY	USED ON

MATL ENGR

APPLICATION

.025

Ø .092
Ø .180

PRESSURE PORT
RESTRICTED

.180

.260

.085

PRESSURE PORT
OPEN

.094

.320

YUMA PROVING GROUND MODEL E30MT3 PRESSURE TRANSDUCER
TWO MOUNTING CONFIGURATIONS TESTED IN DYNAMIC PRESSURE GENERATOR

PRESSURE TRANSDUCER
CALIBRATION REPORT
MOUNTING SENSITIVITY TEST

YPG MODEL E30MT3   SERIAL NO. 27

PRESSURE PSIG	OUTPUT PICOCOULOMBS				AVERAGE OUTPUT	MAX. DEV. %
	(1)	(2)	(3)	(4)		
30000	9169	9195	9209	9241	9204	0.40
40000	12220	12270	12290	12380	12290	0.73
50000	15270	15320	15330	15490	15350	0.90
60000	18320	18390	18440	18580	18430	0.81
70000	21380	21440	21470	21490	21440	0.23

(1) FULL THERMAL PROTECTION-24 HOLE THERMAL CAP-OPEN PRESSURE PORT

(2) FULL THERMAL PROTECTION-24 HOLE THERMAL CAP-RESTRICTED PRESSURE PORT

(3) THERMAL CAP ONLY-RESTRICTED PRESSURE PORT

(4) FULL THERMAL PROTECTION-24 HOLE THERMAL CAP-RESTRICTED PRESSURE PORT-
    PRESSURE PORT FILLED WITH GREASE (PENZOIL 705)

PRESSURE TRANSDUCER
CALIBRATION REPORT
MOUNTING SENSITIVITY TEST

YPG MODEL E30MT3   SERIAL NO. 25

PRESSURE PSIG	OUTPUT PICOCOULOMBS			AVERAGE OUTPUT	MAX. DEV. %
	(1)	(2)	(3)		
30000	9480	9490	9490	9487	0.07
40000	12670	12680	12680	12680	0.08
50000	15810	15840	15830	15830	0.13
60000	18950	19000	19020	18990	0.21
70000	22080	22140	22150	22120	0.18

(1) FULL THERMAL PROTECTION-20 HOLE THERMAL CAP-RESTRICTED PRESSURE PORT

(2) FULL THERMAL PROTECTION-20 HOLE THERMAL CAP-OPEN PRESSURE PORT

(3) FULL THERMAL PROTECTION-24 HOLE THERMAL CAP-OPEN PRESSURE PORT

MODEL NO. E30MT3

SERIAL NO. 27

PRESSURE PORT OPEN

7705

6164

4623

3082

1541

0 .1 .2 .3 .4 .5 .6

TIME IN MILLISEC
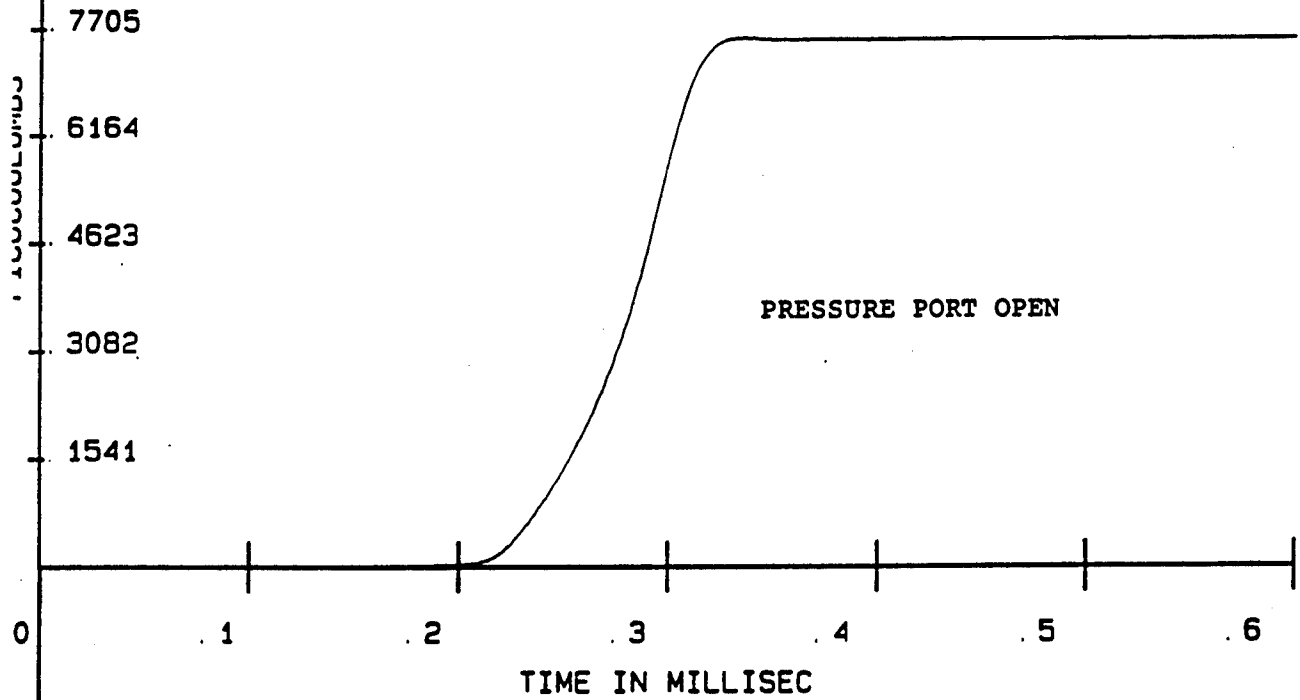
CHARGE OUTPUT = 7708

PRESSURE = 29844 psi

RISETIME = 740 usec

YPG BALLISTIC TRANSDUCER LAB

02-19-93

MODEL NO. E30MT3
SERIAL NO. 27

10870

8696

6522

PRESSURE PORT OPEN

4348

2174

.1   .2   .3   .4   .5   .6

TIME IN MILLISEC
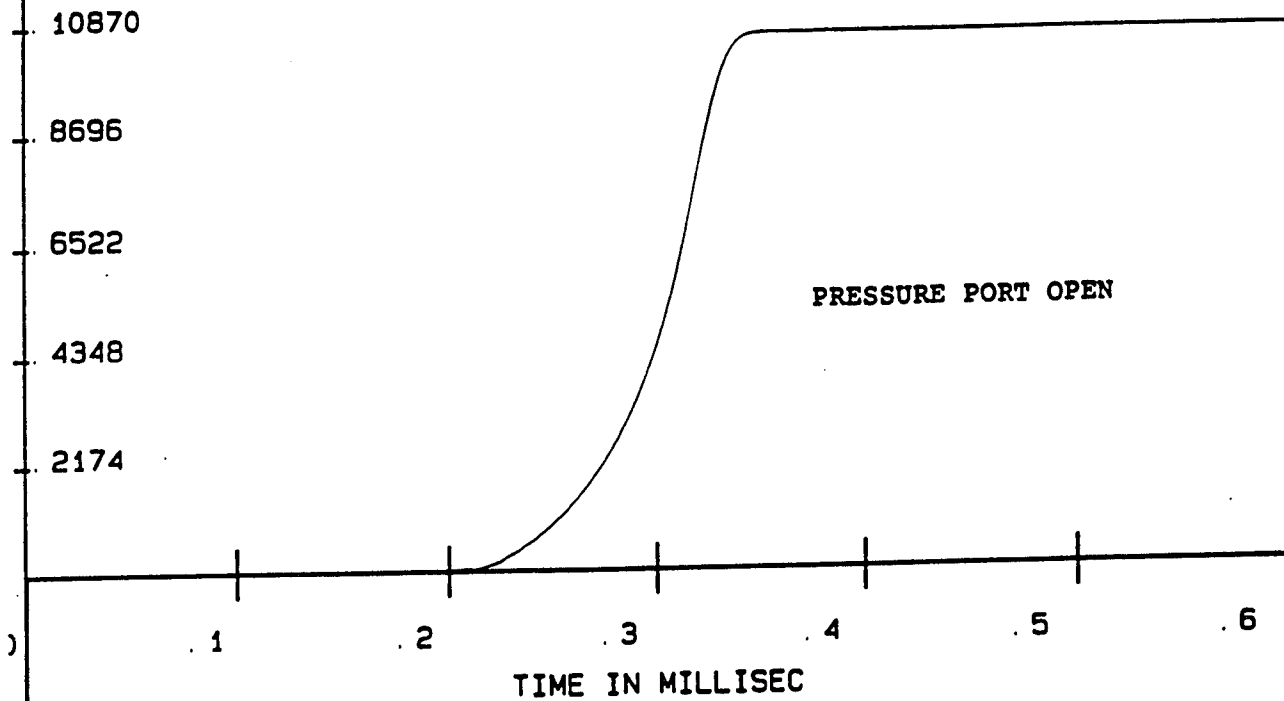
CHARGE OUTPUT = 10871
PRESSURE = 69692 psi
RISETIME = 760 usec

160

02-19-93

MODEL NO. E30MT3

SERIAL NO. 27

PRESSURE PORT RESTRICTED

TIME IN MILLISEC
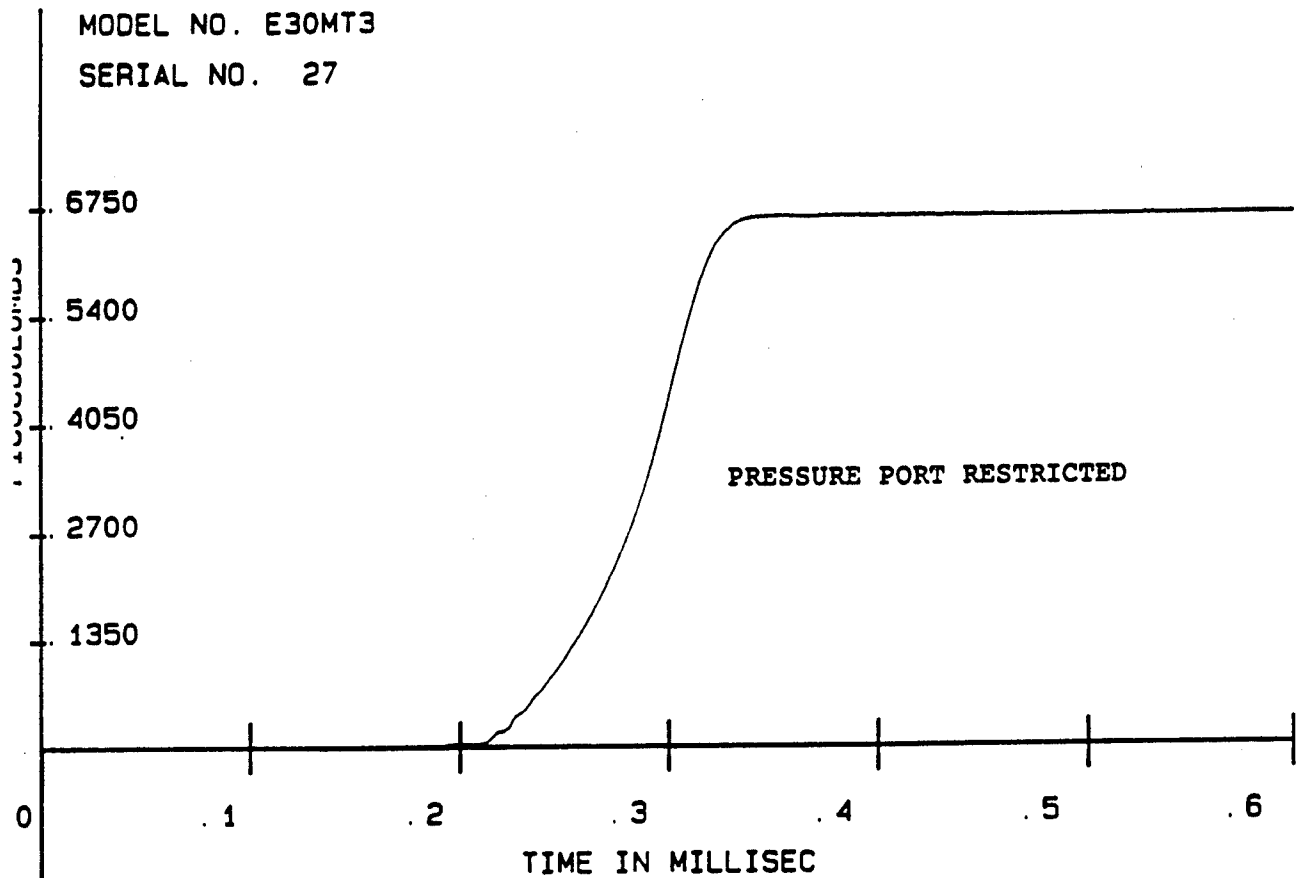
CHARGE OUTPUT = 6752

PRESSURE = 29870 psi

RISETIME = 800 usec

YPG BALLISTIC TRANSDUCER LAB

02-19-93

MODEL NO. E30MT3

SERIAL NO. 27

8495

6796

5097

3398

1699

PRESSURE PORT RESTRICTED

TIME IN MILLISEC

0   .1   .2   .3   .4   .5   .6
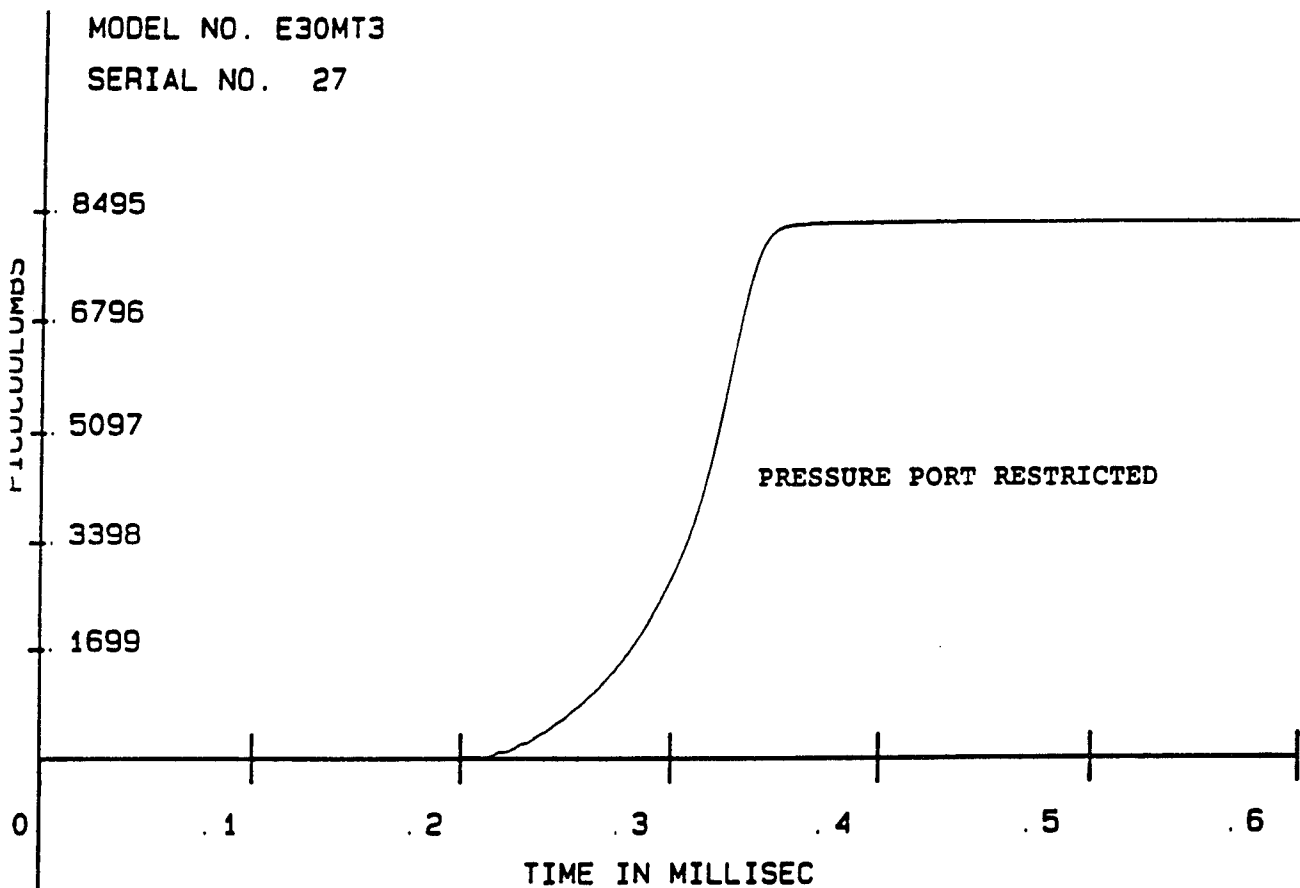
CHARGE OUTPUT = 8496

PRESSURE = 69777 psi

RISETIME = 820 usec

02-22-93

MODEL NO. E30MT3

SERIAL NO. 27

30,000 PSI

9275

7420

PRESSURE PORT RESTRICTED

(WITH GREASE)

5565

3710

1855

.1   .2   .3   .4   .5   .6

TIME IN MILLISEC
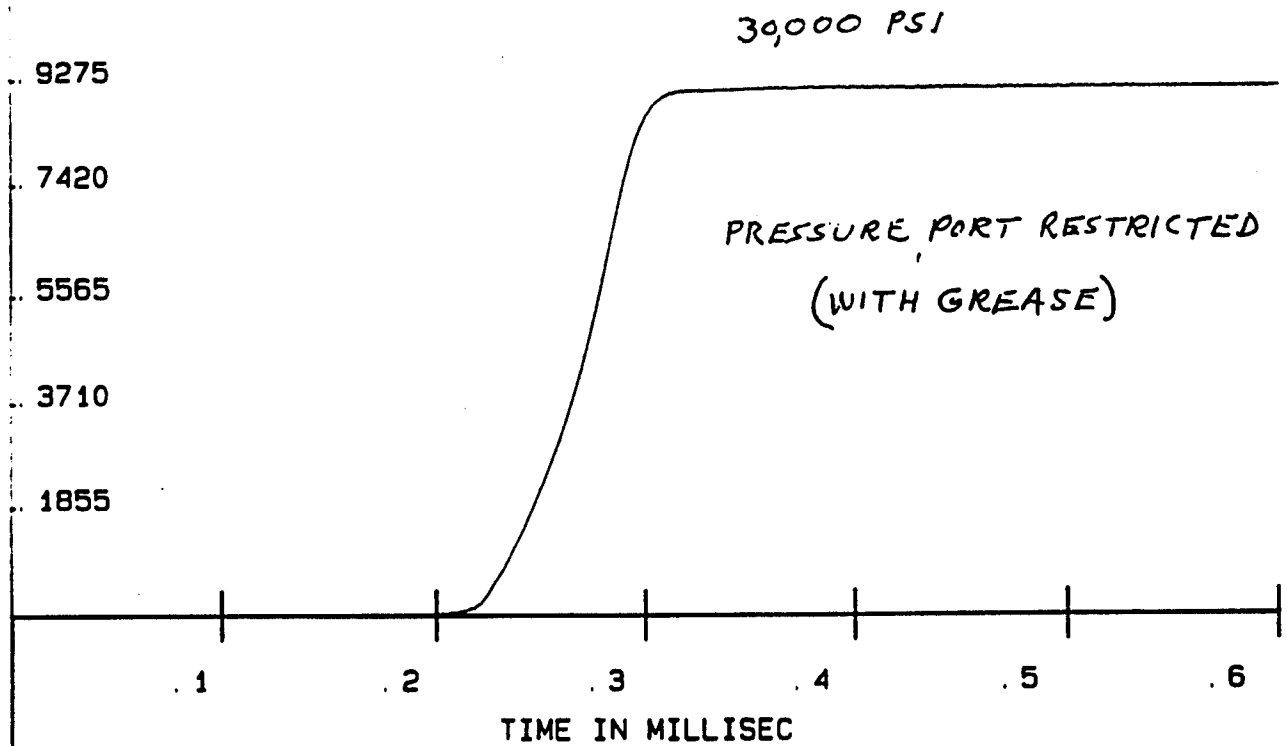
RISETIME = 630 usec

02-22-93

MODEL NO. E30MT3

SERIAL NO. 27

70,000 PSI

PRESSURE PORT RESTRICTED
(WITH GREASE)

. 18785

. 15028

. 11271

. 7514

. 3757

. 1   . 2   . 3   . 4   . 5   . 6

TIME IN MILLISEC
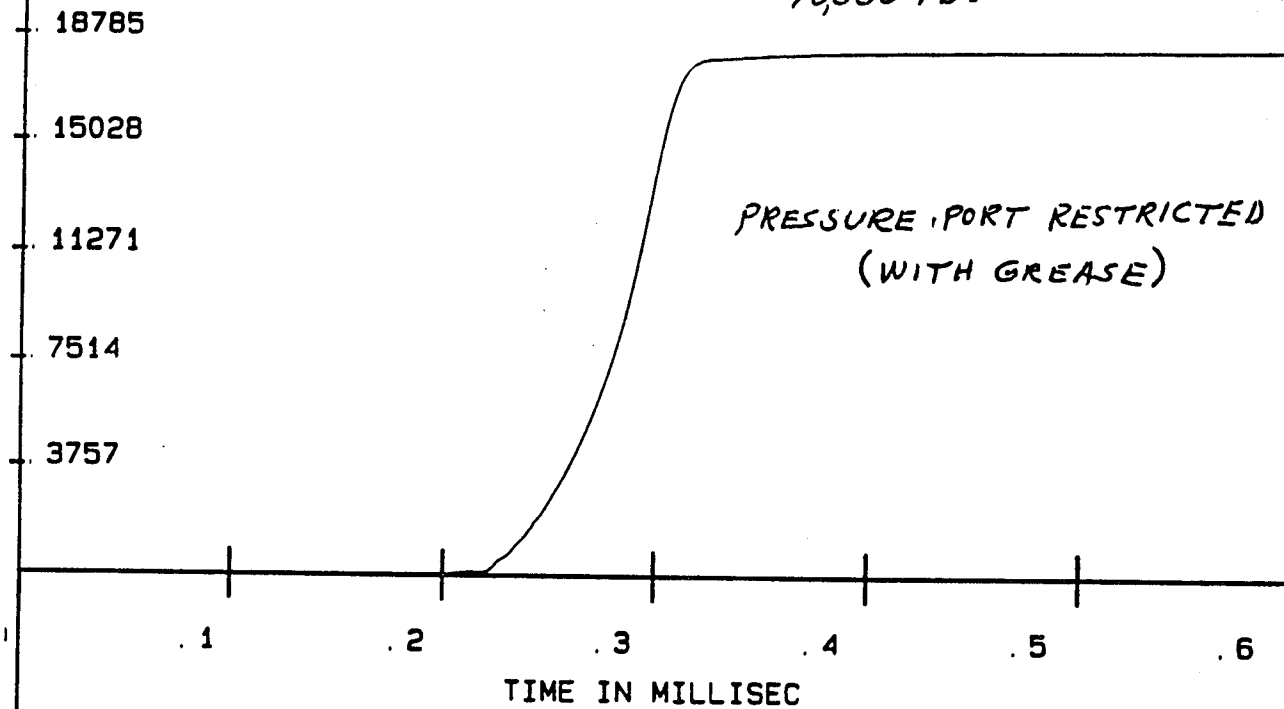
RISETIME = 640 usec

APPENDIX H:

PRESENTATION - "FIBER OPTIC PRESSURE TRANSDUCERS"

*This Appendix is presented in its original form without
editorial changes or comments.*

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UNITED STATES ARMY
COMBAT SYSTEMS TEST ACTIVITY

COMBAT SYSTEMS TEST ACTIVITY

tester of choice
tester of choice
tester of choice
tester of choice
tester of choice
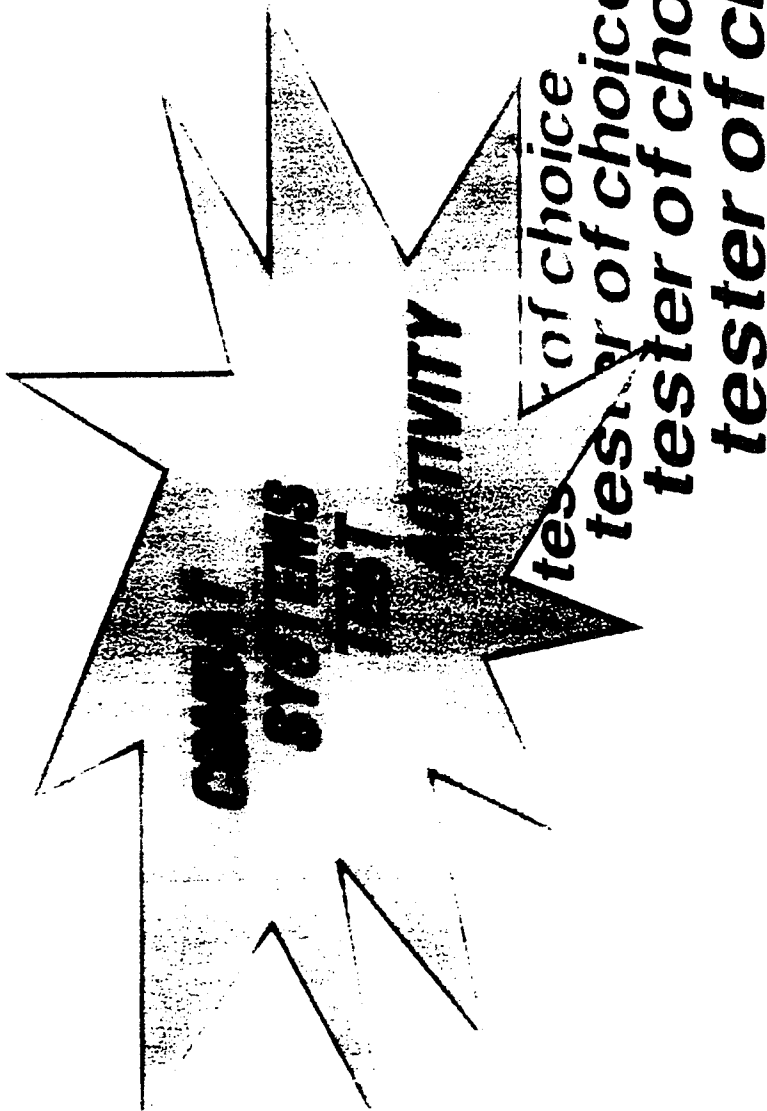
Fiber Optic Pressure Transducers
W. Scott Walton

Fiber Optic Pressure Transducers

Challenges

- Immature technology

- Rapidly changing

- Proprietary

Fiber Optic Pressure Transducers
SBIR Efforts

ARDEC — Quest Integrated (Phase I & II)

Eglin AFB — Physical Sciences, Inc
- Nova Sensor
- Geo-Centers

DNA -Geo-Centers (Phase 1.5)

ARL -LightWave Electronics (Phase I & II)
-MIT (STAS effort)

CSTA -KMS Fusion
-TACAN
-Geo-Centers (Phase 1.5)
-Quest Integrated (Phase I & II)

Fiber Optic Pressure Transducer

TACAN Corporation

- Semi-conductor absorption probe

- No moving parts

- Static demonstration: 10,000 psi (69 MPa)

Pressure

Fiber

Coupler

Source

Receiver

Signal Processing

Semiconductor Coating

Mirror Coating

Fiber

Enlarged View of End of Fiber

TACAN Corporation

171
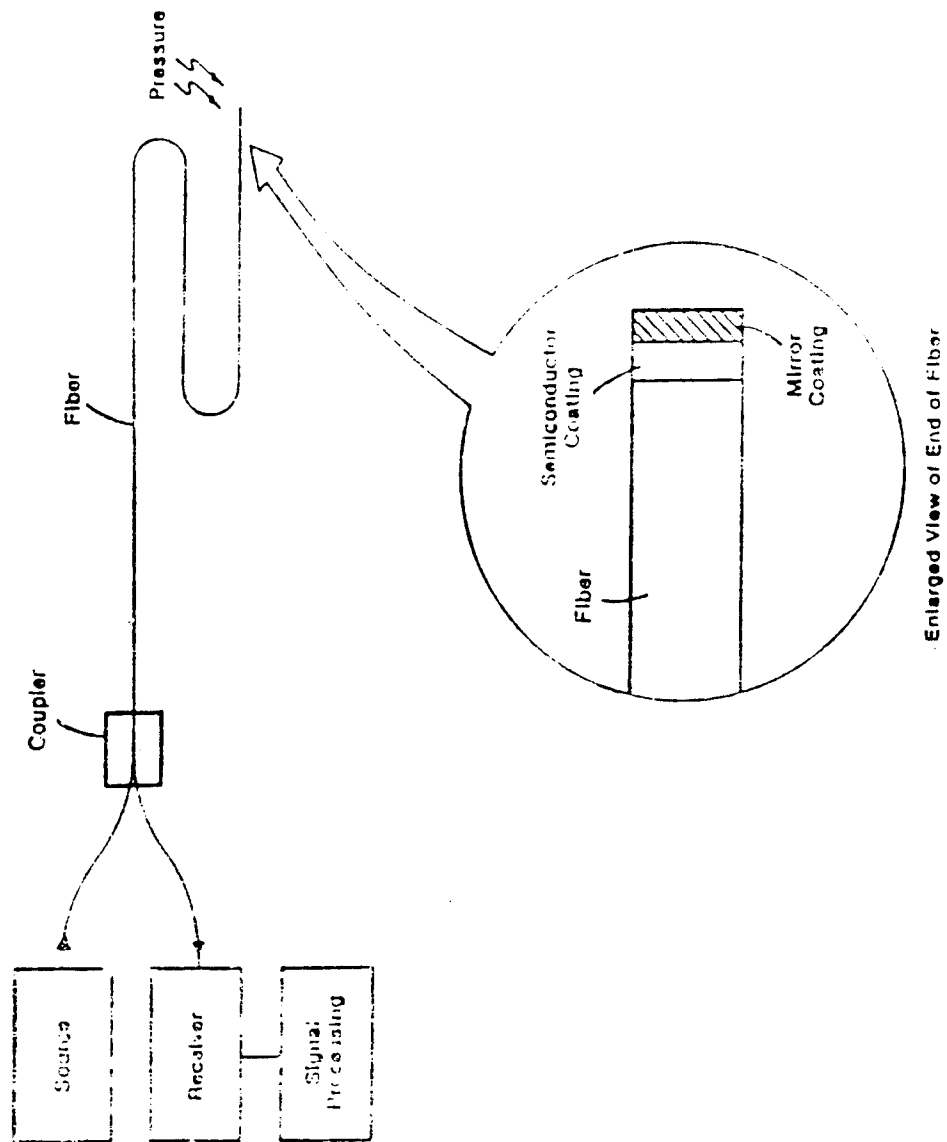
Fiber Optic Pressure Transducers

Geo-Centers, Inc.

- Photoelastic Effect

- Piston & optical components in transducer

- Dynamic Demonstration to 58,000 psi (400 MPa)

- First measurement in a large caliber gun (120mm)

172

Schematic of the Optical Configuration of a Photoelastic Stress Sensor
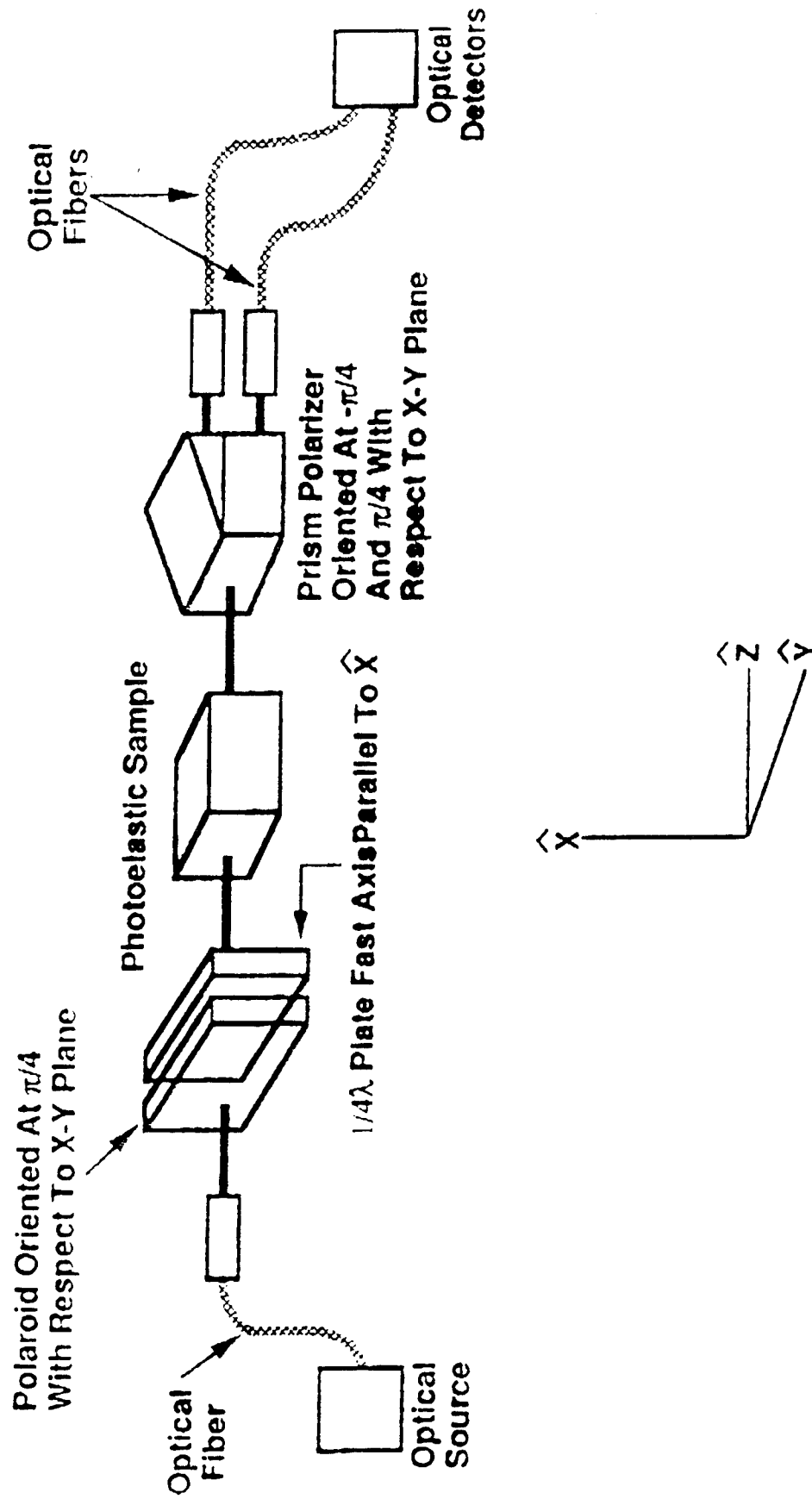
Optical Detectors

Optical Fibers

Prism Polarizer Oriented At $-\pi/4$ And $\pi/4$ With Respect To X-Y Plane

Photoelastic Sample

$1/4\lambda$ Plate Fast Axis Parallel To $\hat{X}$

Polaroid Oriented At $\pi/4$ With Respect To X-Y Plane

Optical Fiber

Optical Source

$\hat{Z}$ $\hat{Y}$ $\hat{X}$
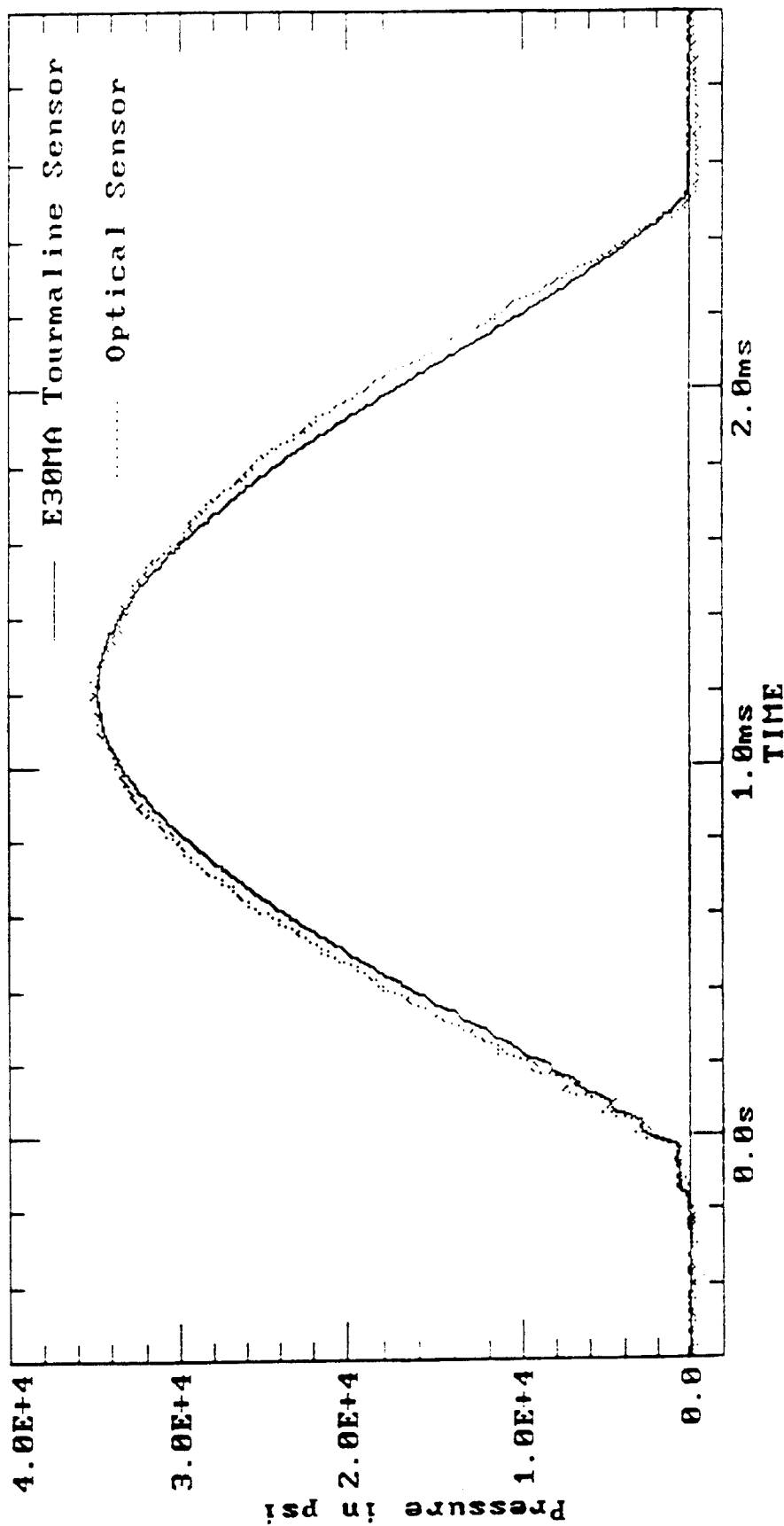
Figure 1. Laboratory test performance of fiber optic pressure transducer. Note excellent agreement with piezoelectric transducer.
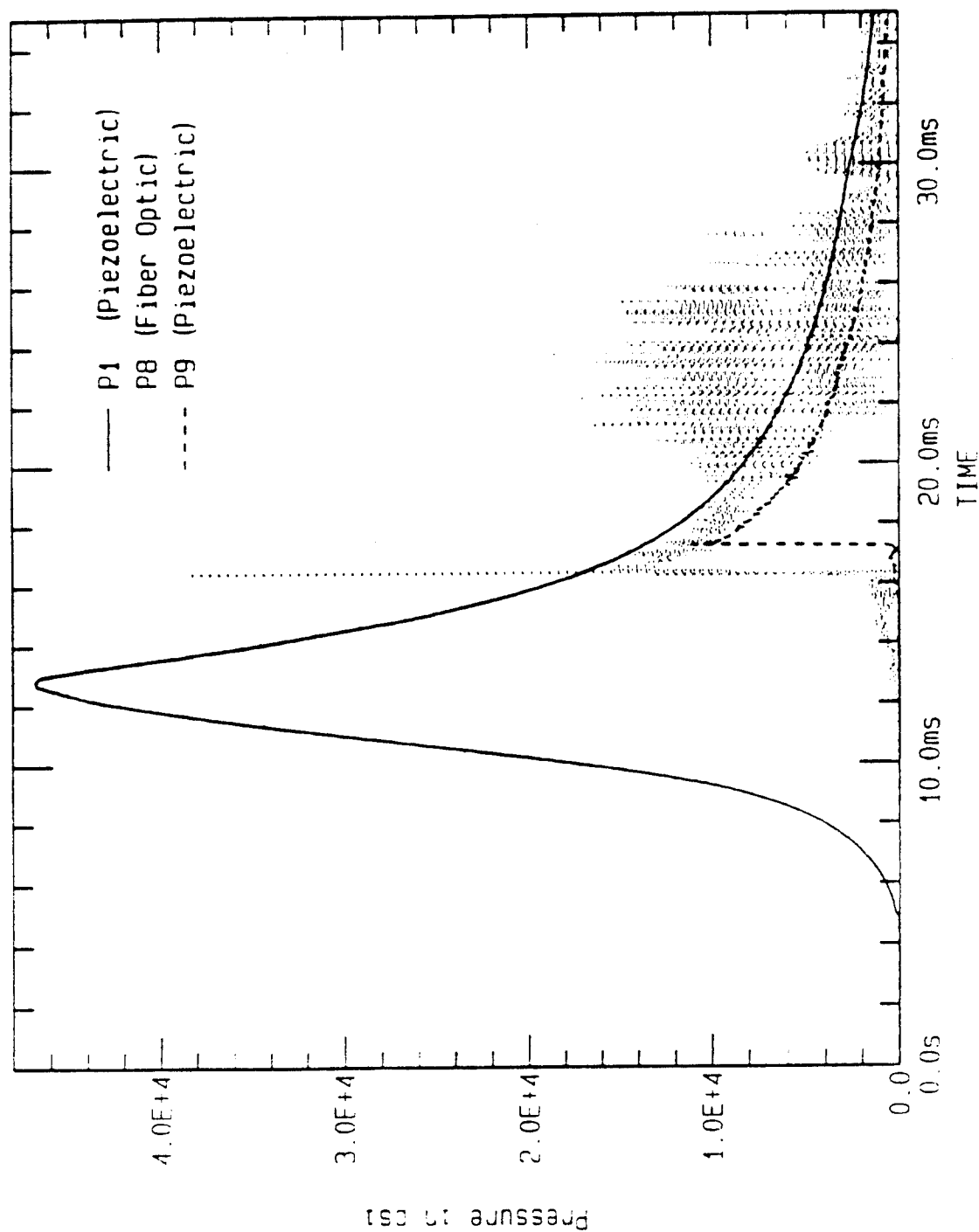
Figure 2. Fiber optic pressure transducer performance in a large caliber gun.

Fiber Optic Pressure Transducer
Quest Integrated, Inc.

- Intensity reduction due to diaphram displacement (US Patent 4,158,310)

- Static demonstration: 140,000 psi (965 MPa)

- Dynamic demonstration: 100,000 psi (690 MPa)

SENSOR HEAD

LIGHT SOURCE

TO DETECTOR

ILLUMINATING FIBERS (SOLID)

RECEIVING FIBERS (OPEN)

SECTION 2-2

FIBER BUNDLE

REFLECTED LIGHT

DIAPHRAGM

ILLUMINATING LIGHT

SECTION 3-3
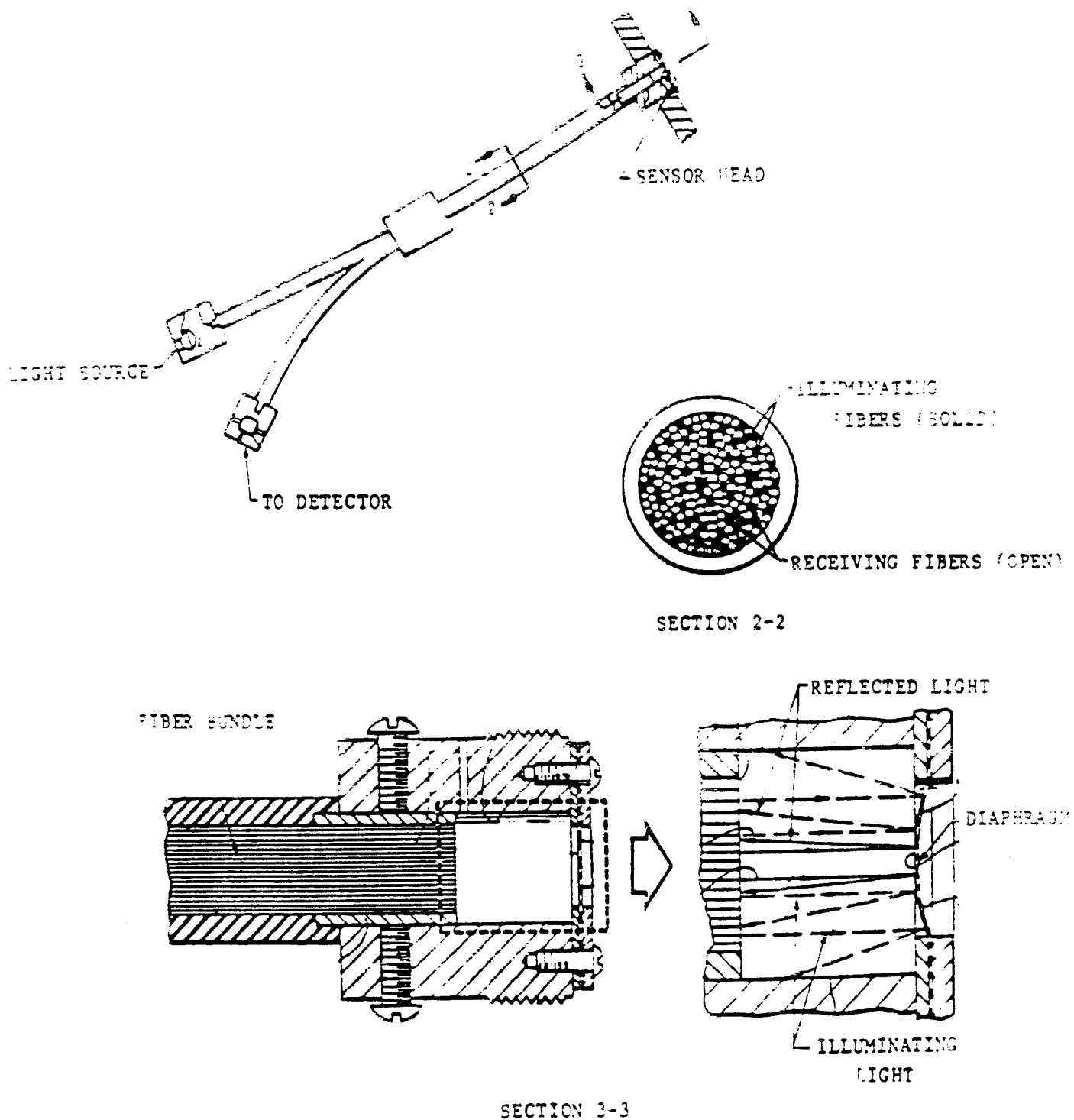
Figure 2.   Schematic of an FOPT with Randomly Distributed Fiber Bundles (U.S. Patent 4,158,310)

Quest Integrated Inc

177
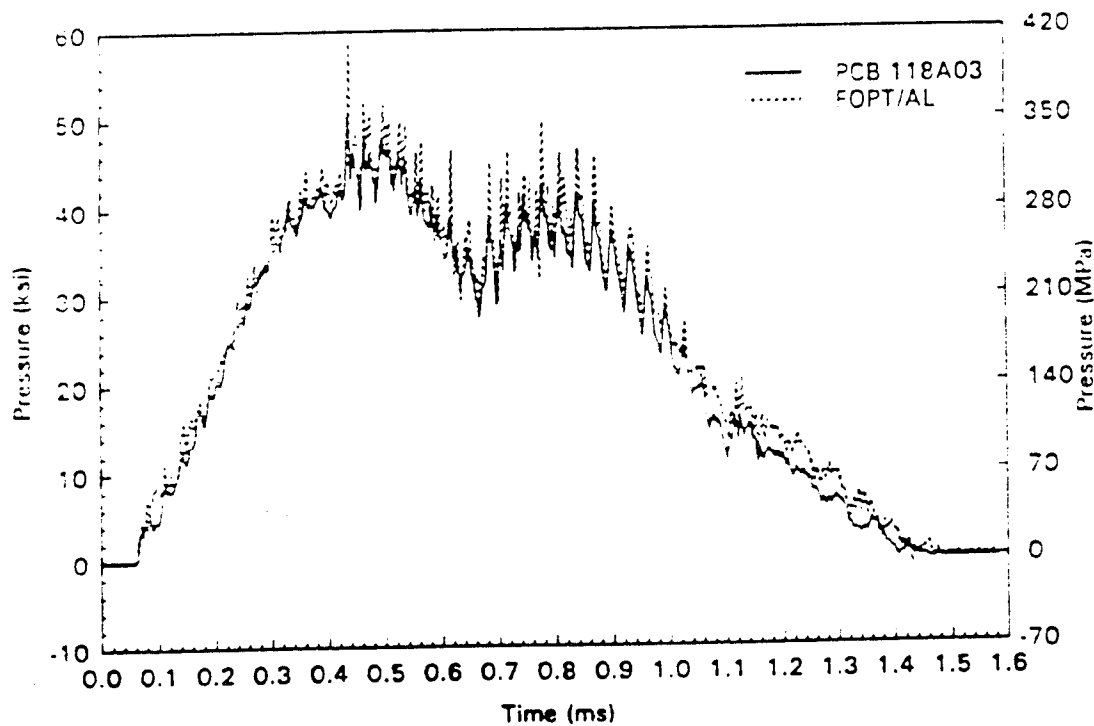
Figure 2. Comparison of the Pressure Pulse Measured Simultaneously with a PCB 118A03 and an FOPT/AL - Peak pressure ≈ 350 MPa (50 ksi) [Figure 16 in Liu et al., 1991].
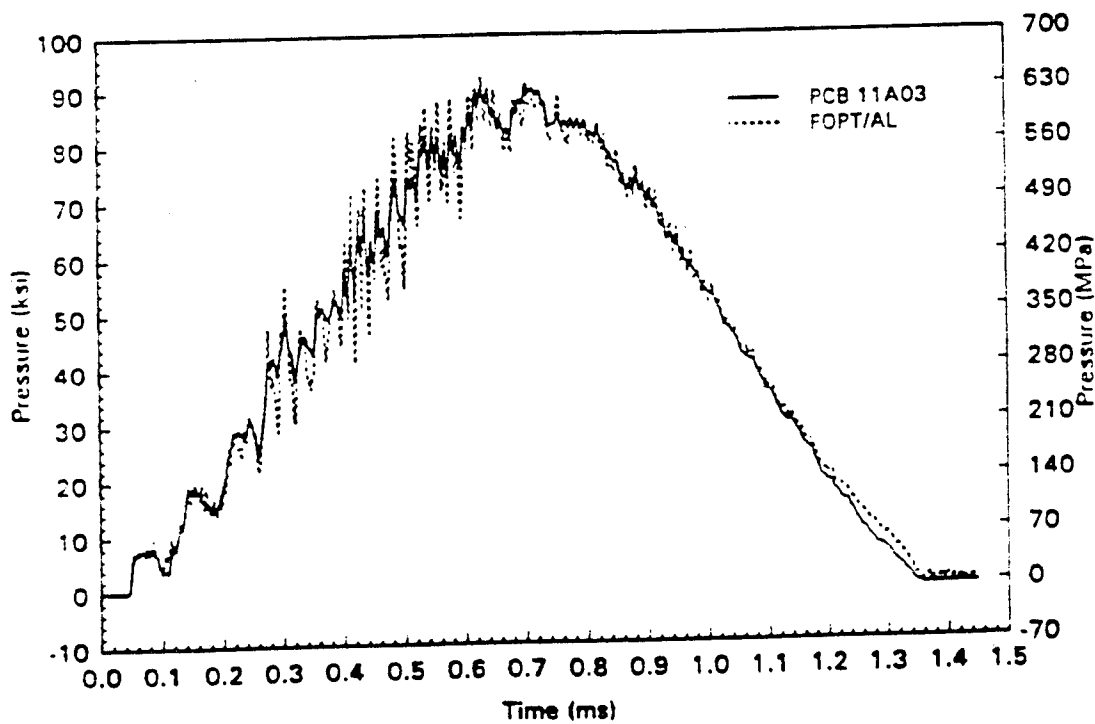
Figure 3. Comparison of the Pressure Pulse Measured Simultaneously with a PCB 118A03 and an FOPT/AL - Peak pressure ≈ 630 MPa (90 ksi) [Figure 17 in Liu et al., 1991].
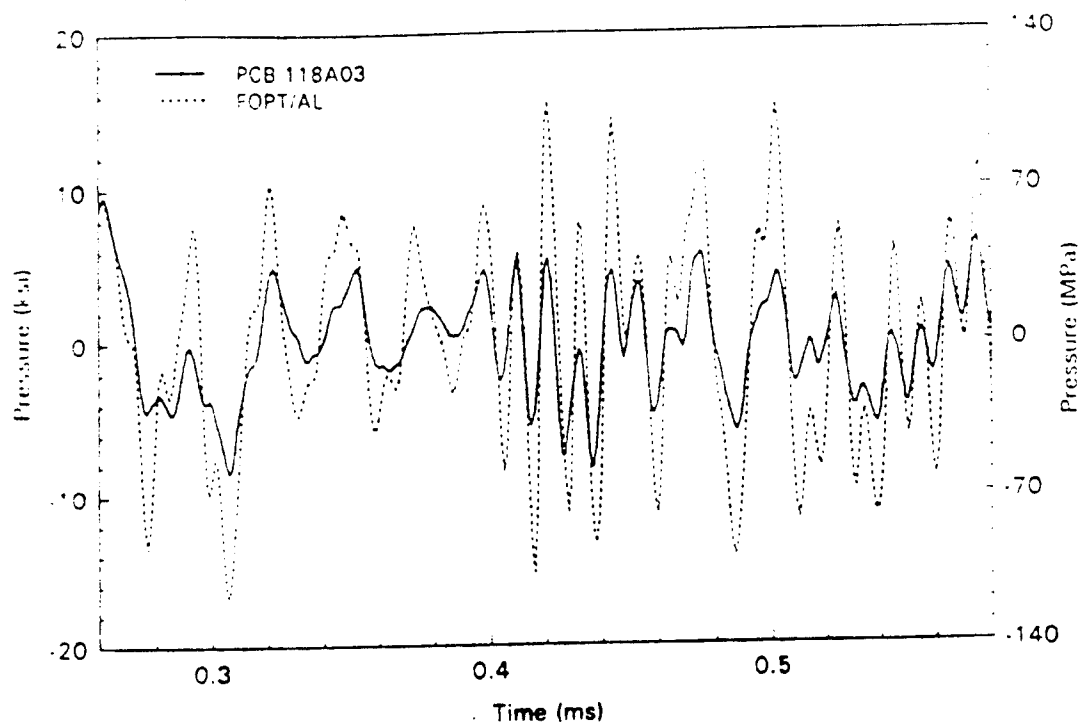
Figure 18. Comparison of the High-Harmonic Components of the Pressure Pulse Measured Simultaneously with a PCB 118A03 and an FOPT/AL - The time series are excerpted from Figure 17 with the linear trend removed.
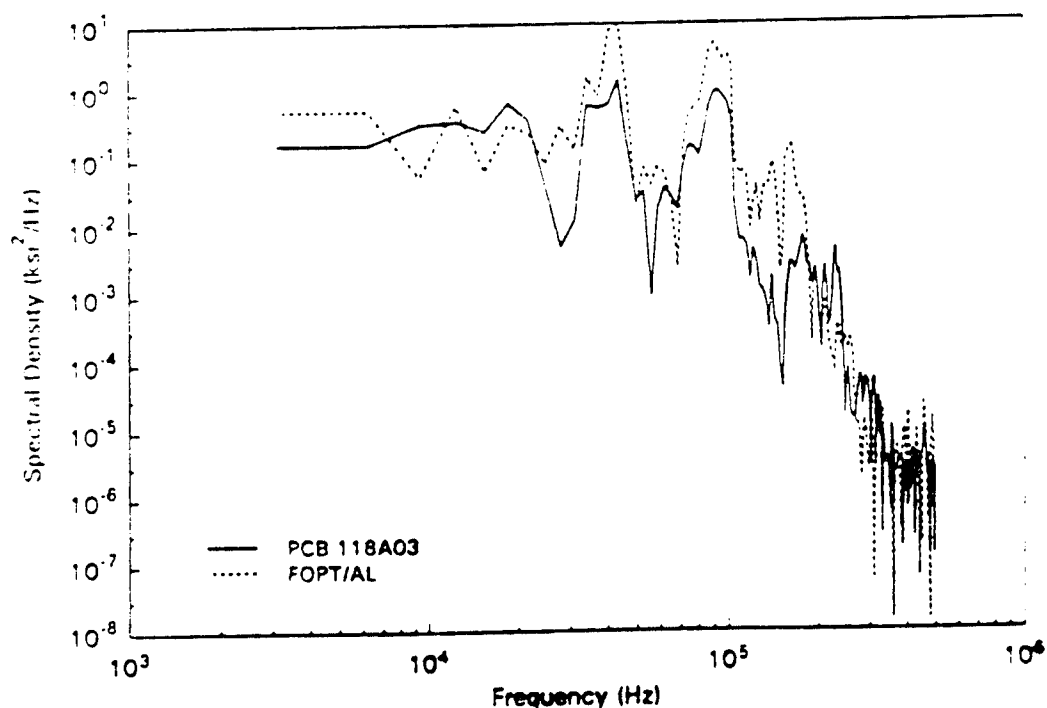
Figure 19. Comparison of the Power Spectra Derived from the Time Series Shown in Figure 18

Fiber Optic Pressure Transducers
Conclusions

- Fiber Optic Isolation
  - Ideal for ET Gun
  - Eliminates ground loop/electrical noise

- Alternate approach for investigating:
  - Pressure oscillations
  - Grease effect

181

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